US 20050179130A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2005/0179130 A1**

Tanaka et al. (43) **Pub. Date: Aug. 18, 2005**

(54) **SEMICONDUCTOR DEVICE**

(76) Inventors: **Hisanori Tanaka**, Anan-shi (JP); **Yasunobu Hosokawa**, Anan-shi (JP); **Yuuki Shibutani**, Anan-shi (JP)

Correspondence Address:
WENDEROTH, LIND & PONACK, L.L.P.
2033 K STREET N. W.
SUITE 800
WASHINGTON, DC 20006-1021 (US)

(21) Appl. No.: **10/920,419**

(22) Filed: **Aug. 18, 2004**

(30) **Foreign Application Priority Data**

Aug. 19, 2003 (JP) 2003-294775

Publication Classification

(51) **Int. Cl.**[7] **H01L 23/04**; H01L 21/48

(52) **U.S. Cl.** **257/730**; 438/125

(57) **ABSTRACT**

A substrate (**10**) has at least one recess (**20**) and/or protrusion (**21**) formed on the surface thereof so as to scatter or diffract the light generated in an active layer (**12**). The recess and/or protrusion is formed in such a shape that can reduce crystalline defect in semiconductor layers (**11, 13**).

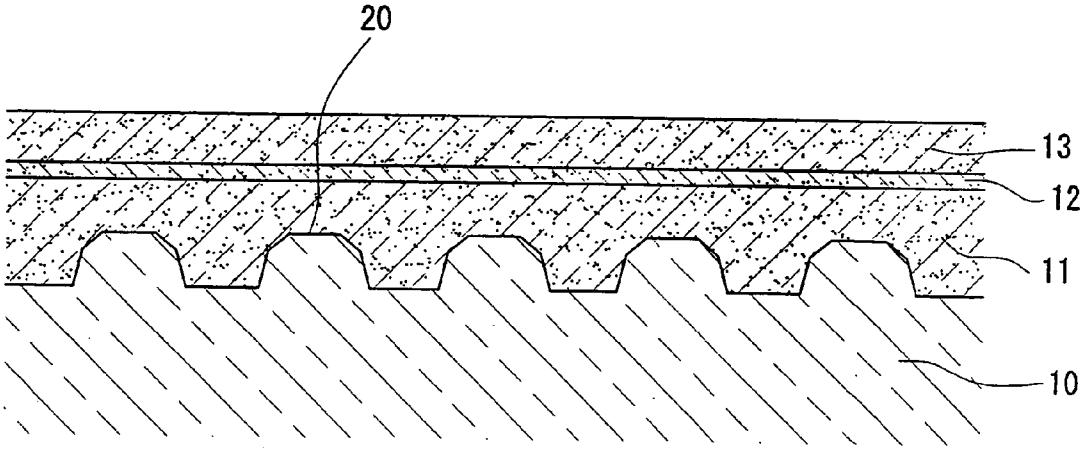


Fig. 1

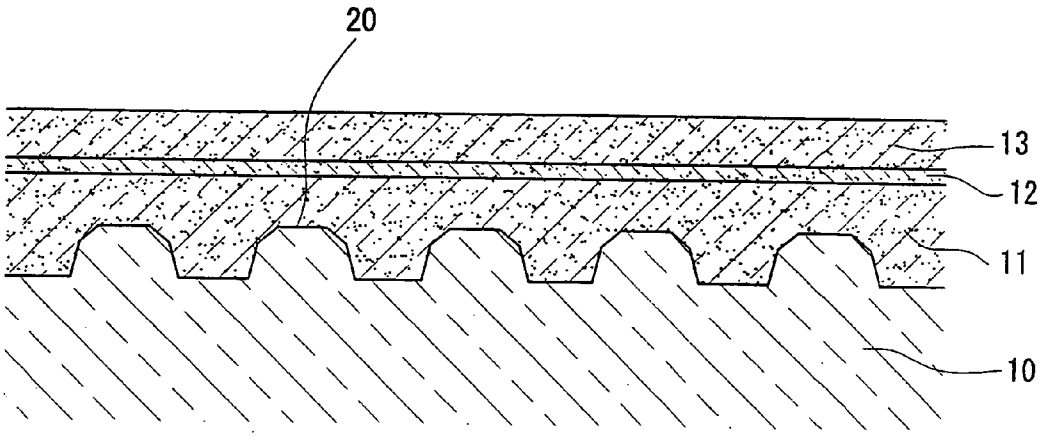


Fig. 2A

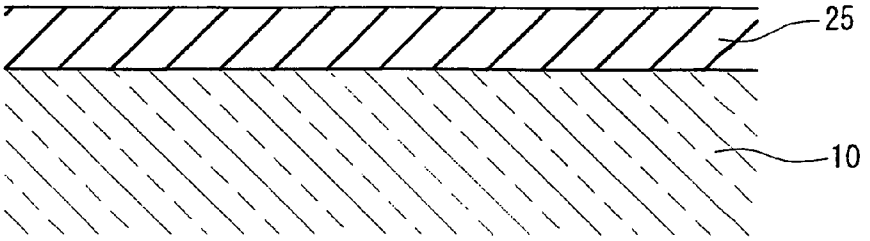


Fig. 2B

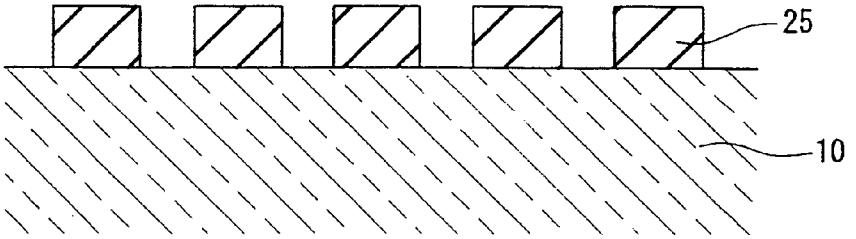


Fig. 2C

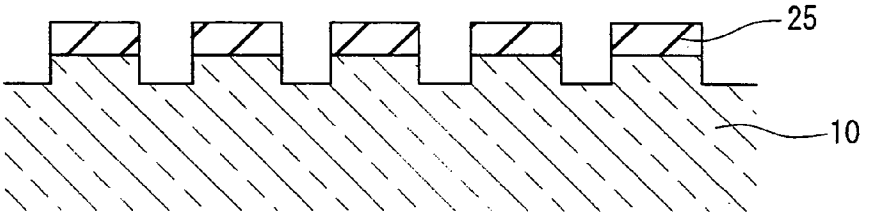


Fig. 2D

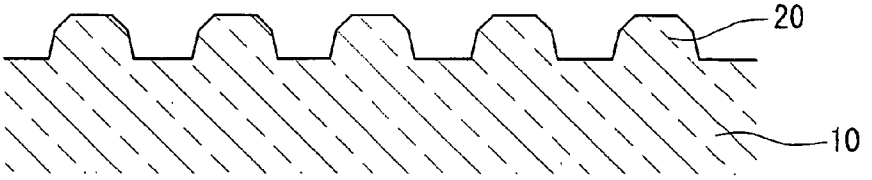


Fig. 2E

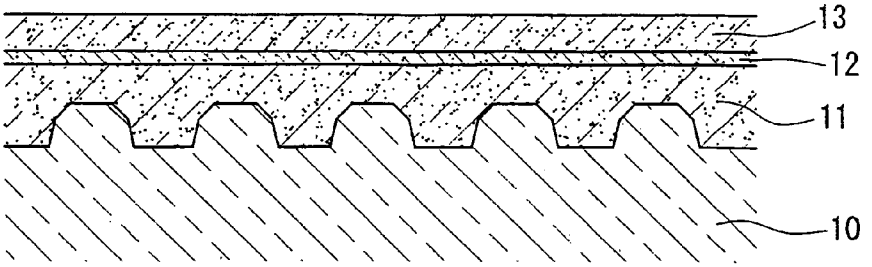


Fig.3A

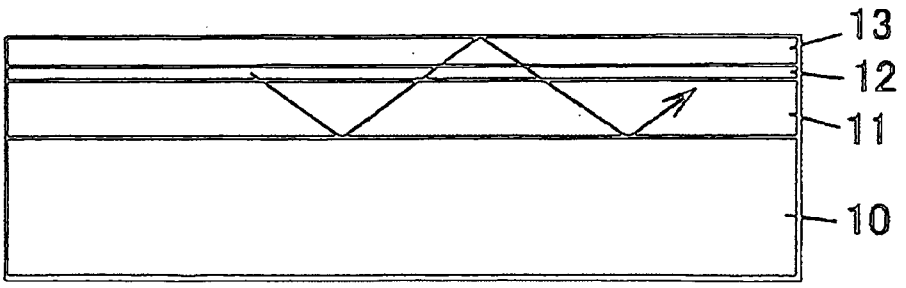


Fig.3B

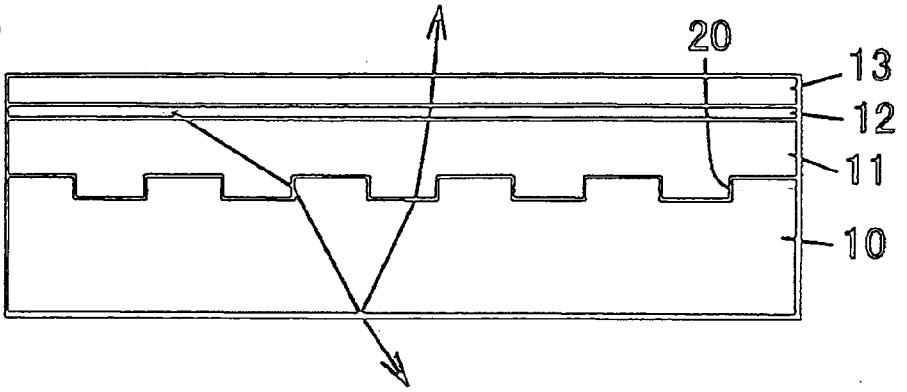


Fig.3C

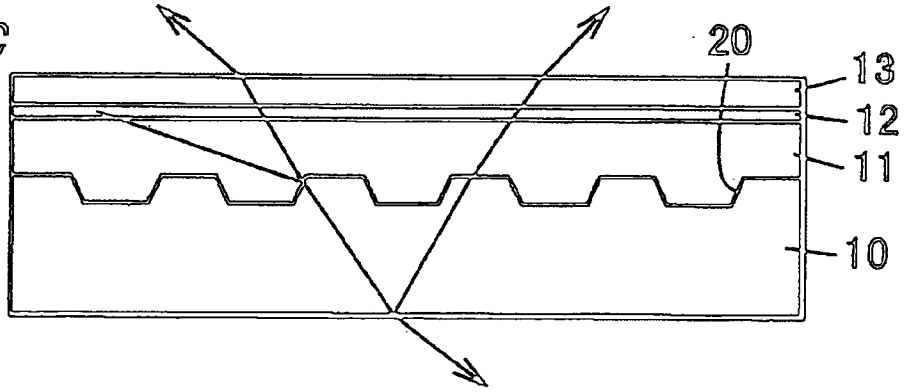


Fig.3D

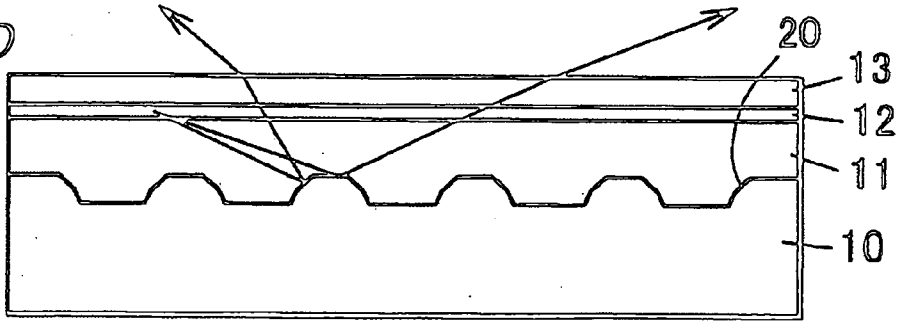


Fig. 4A

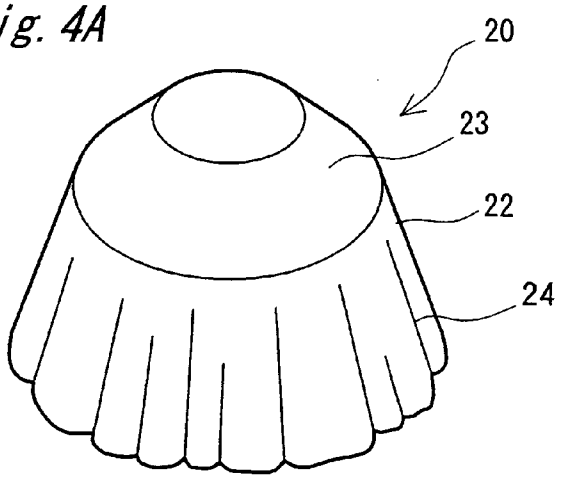


Fig. 4B

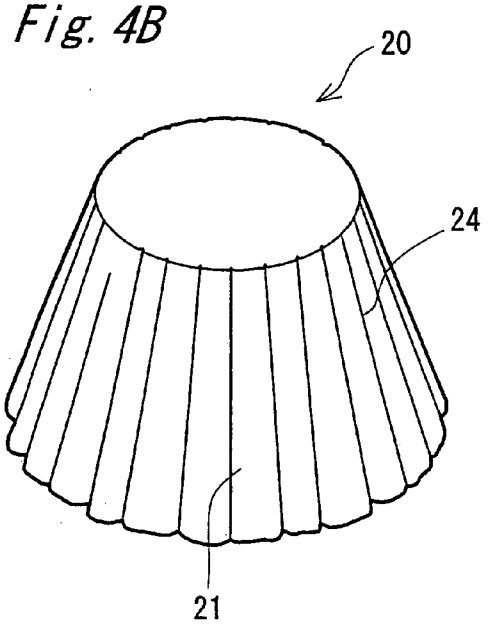


Fig. 4C

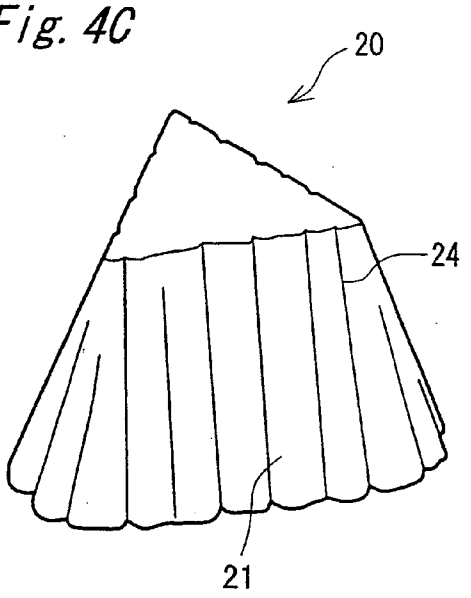


Fig. 5A

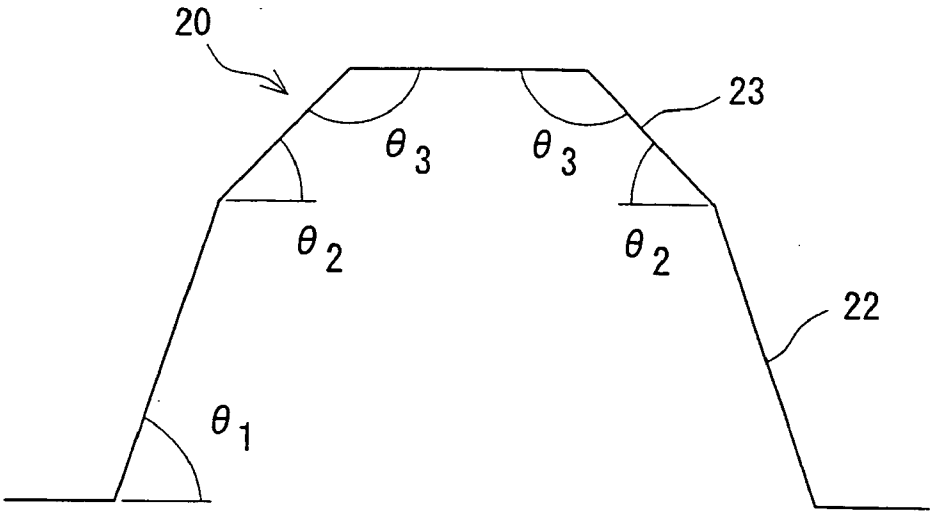


Fig. 5B

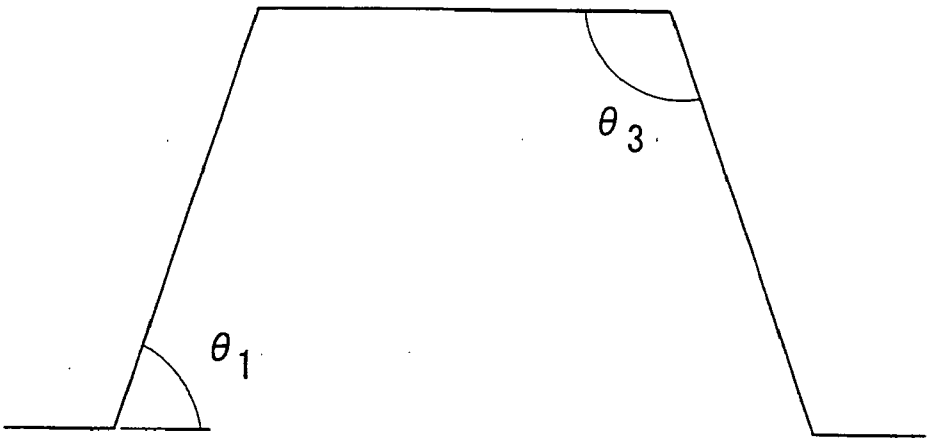


Fig. 6

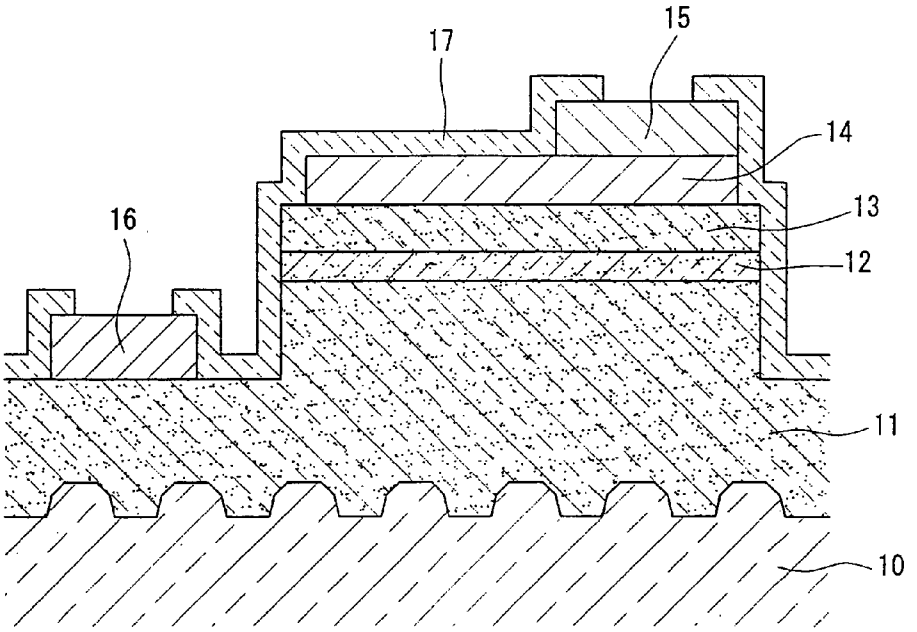


Fig. 7A

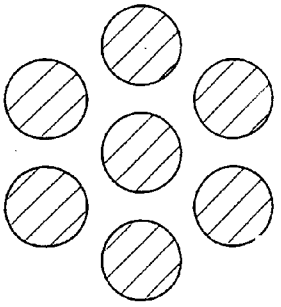


Fig. 7B

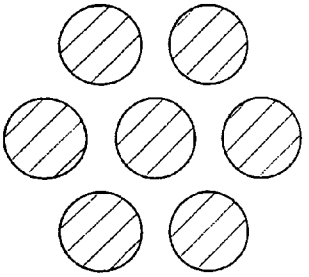


Fig. 7C

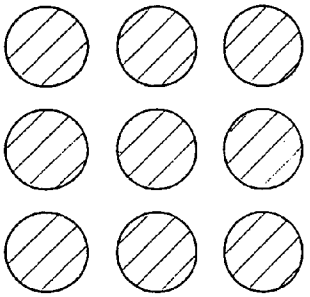


Fig. 7D

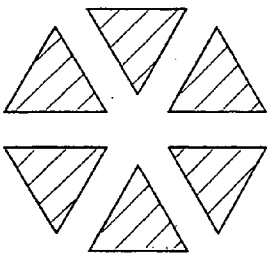


Fig. 7E

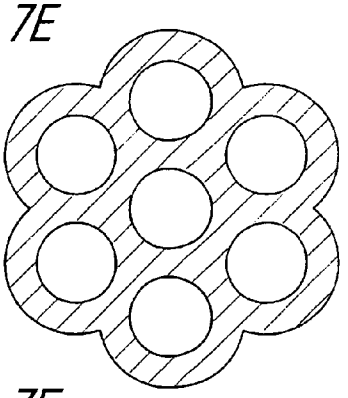


Fig. 7F

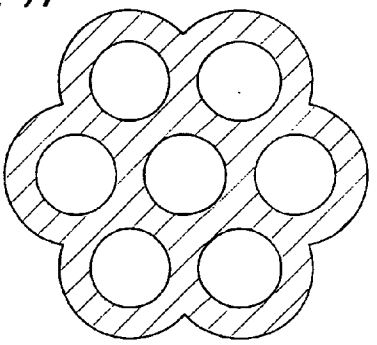


Fig. 7G

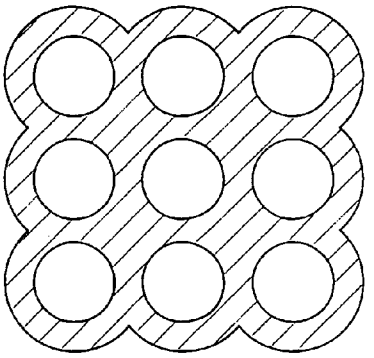


Fig. 7H

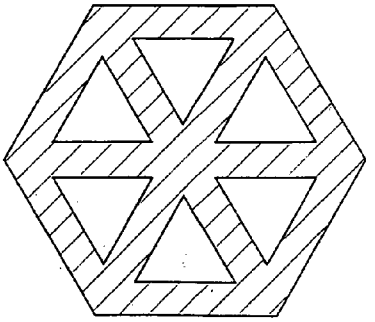


Fig.8A

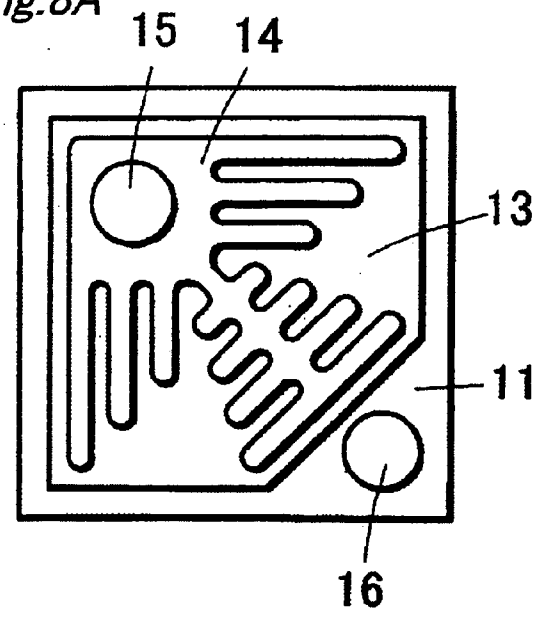


Fig.8B

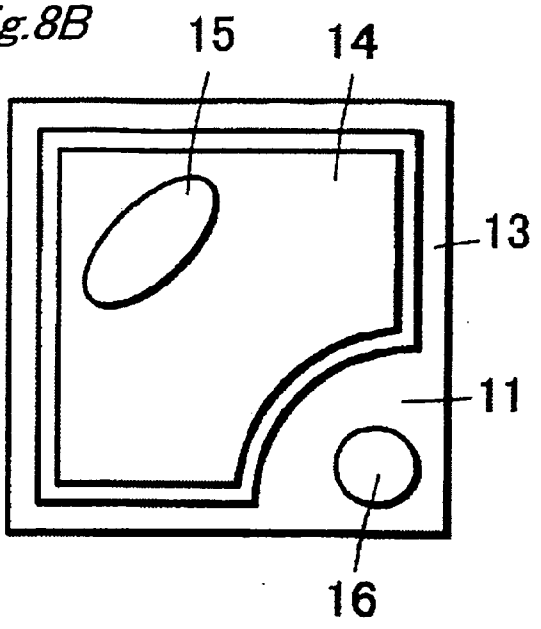


Fig.8C

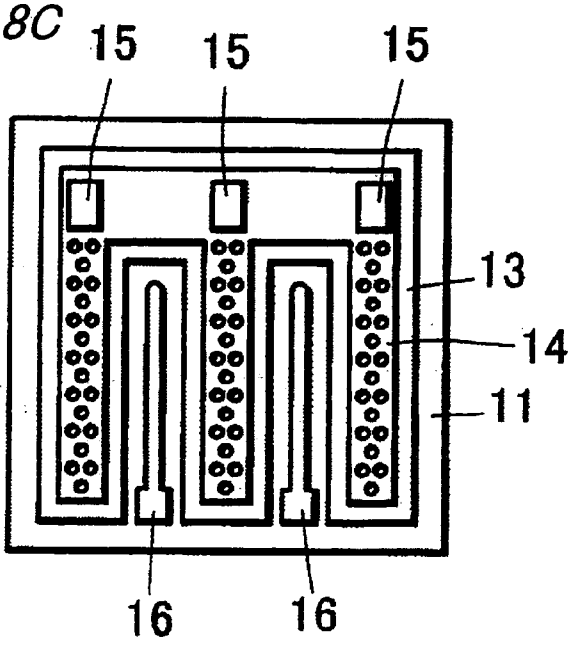


Fig.9A

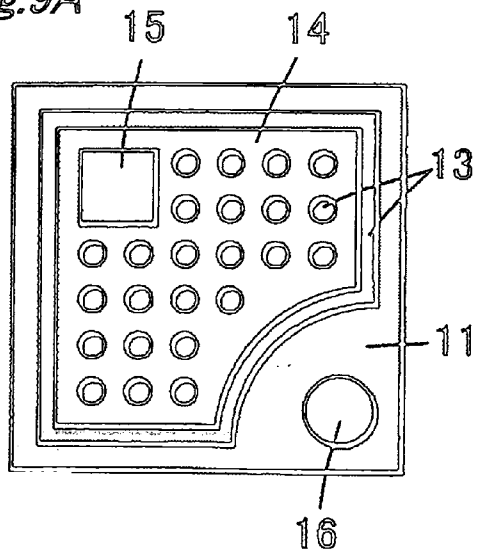


Fig.9B

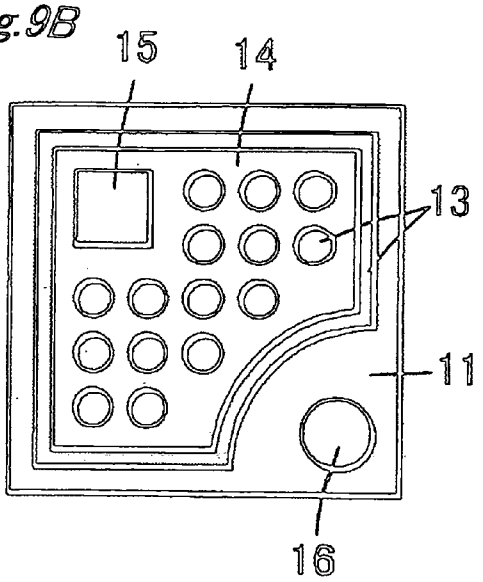


Fig.9C

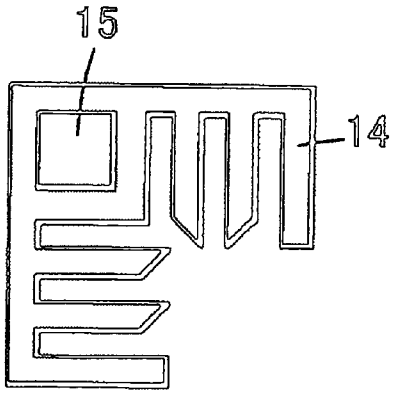


Fig.9D

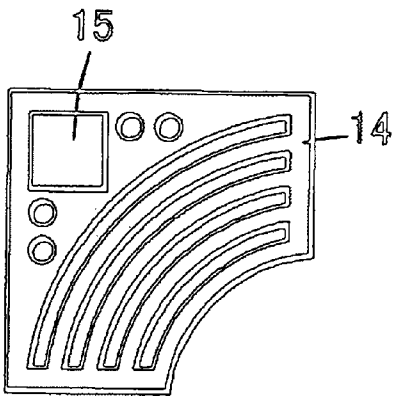


Fig. 10A

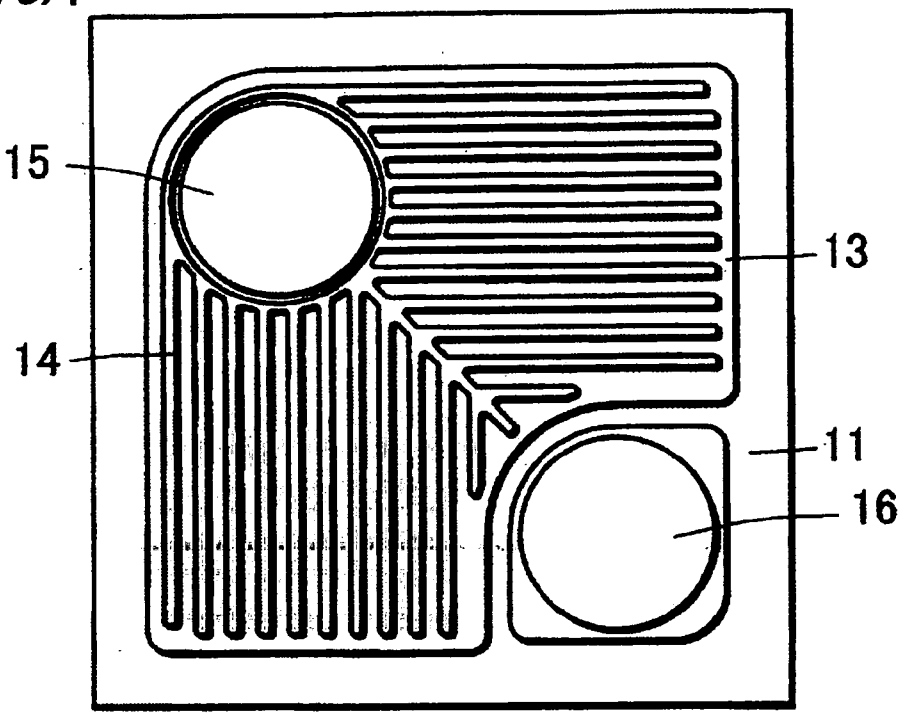


Fig. 10B

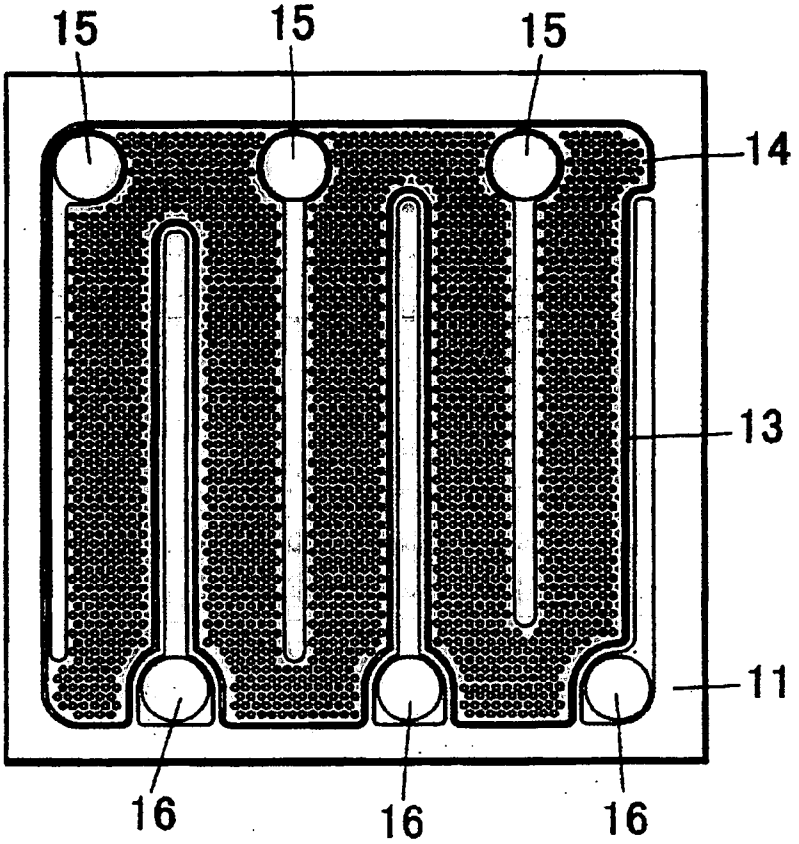


Fig. 11A

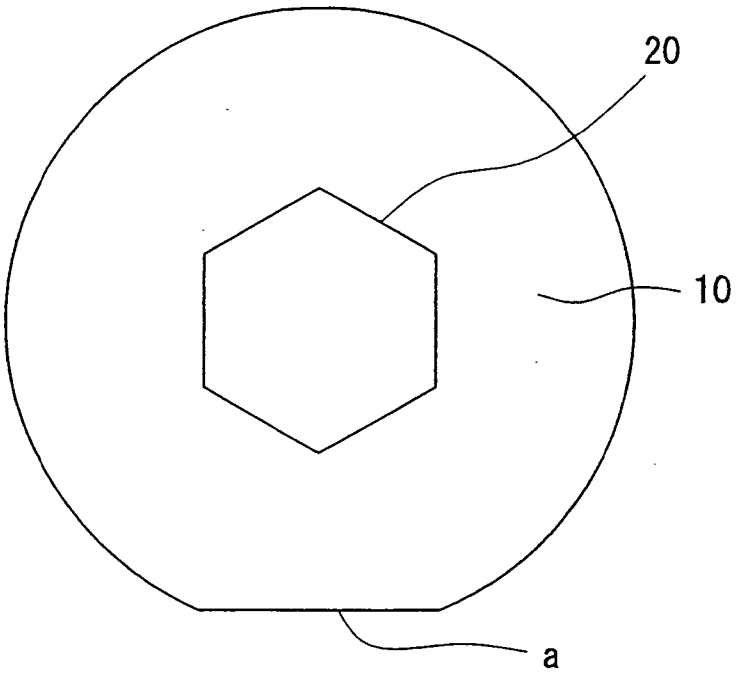


Fig. 11B

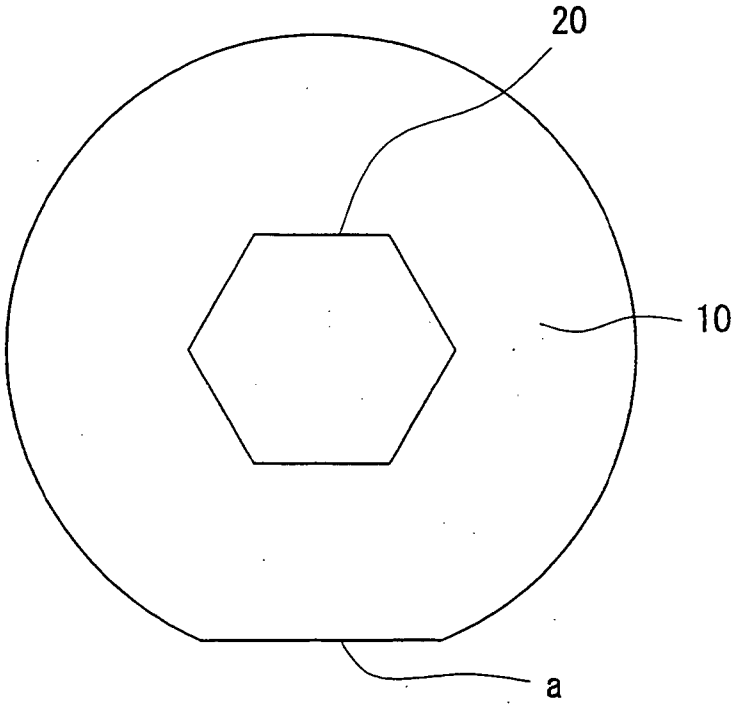


Fig. 12

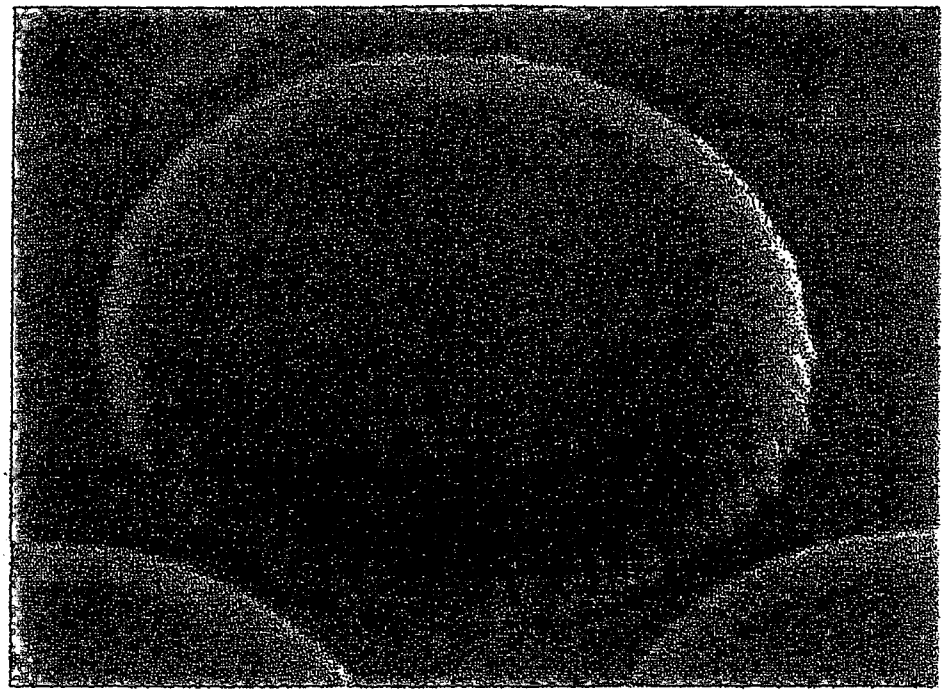


Fig. 13

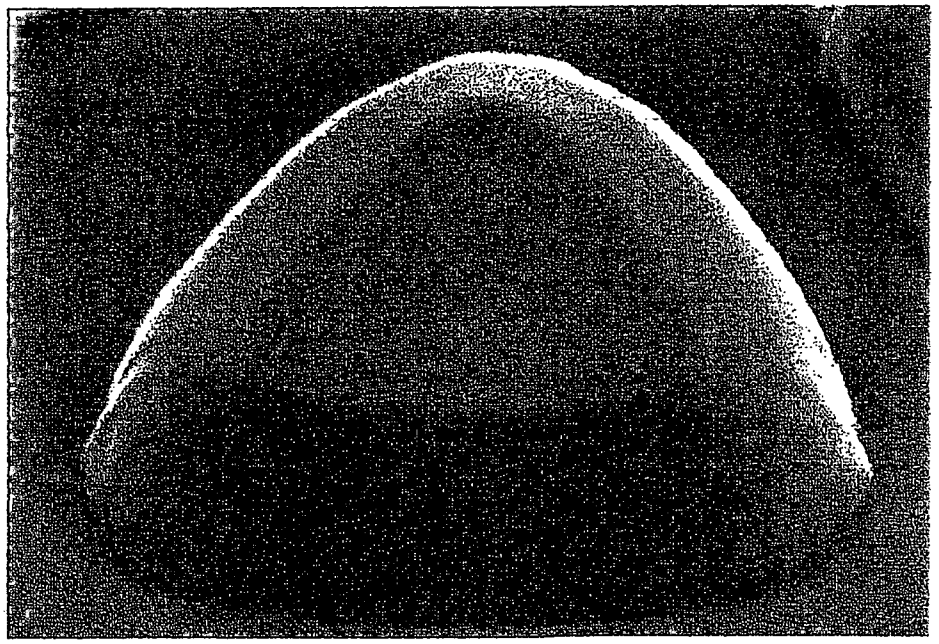


Fig. 14

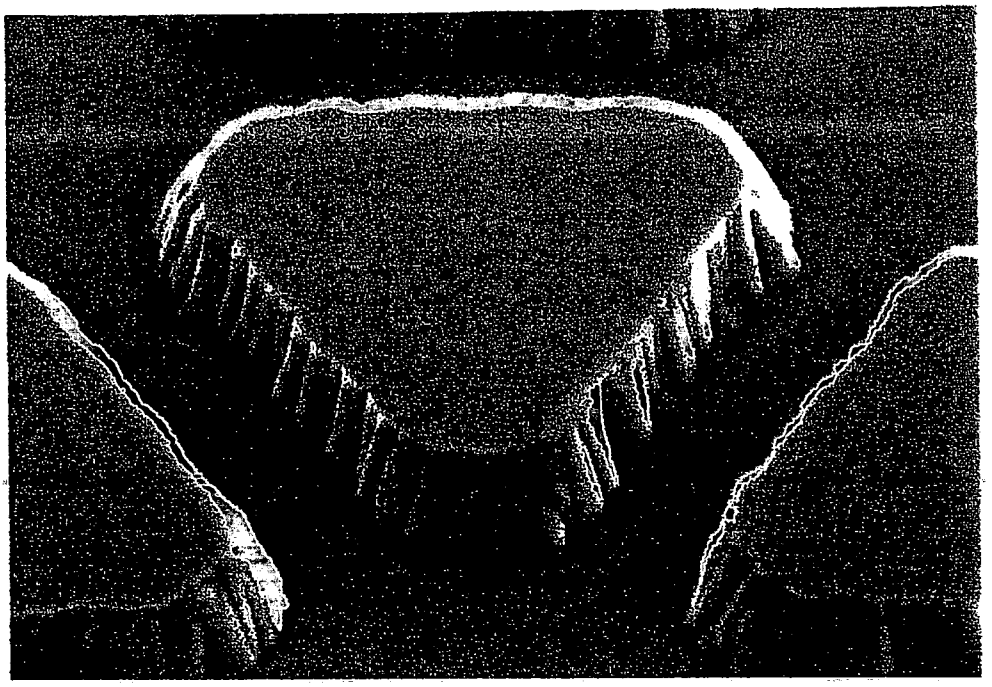


Fig. 15

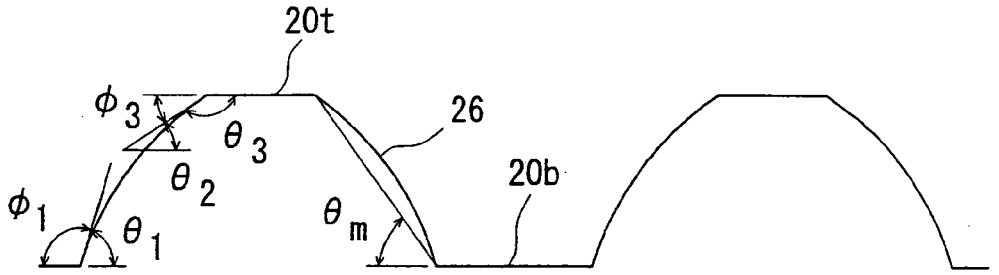


Fig. 16A

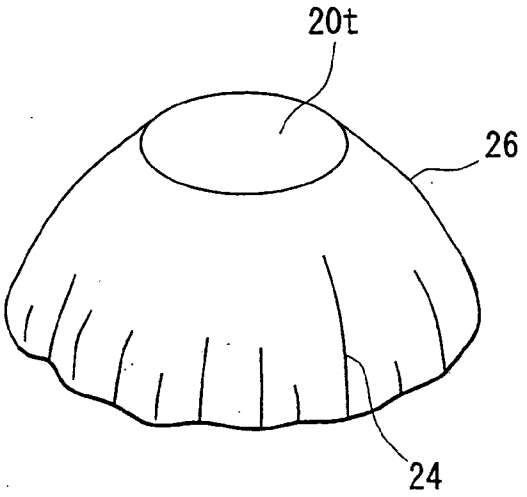


Fig. 16B

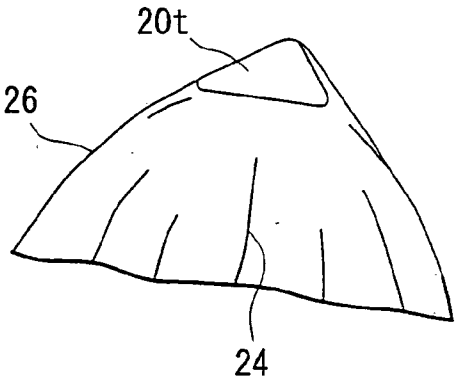


Fig. 17A

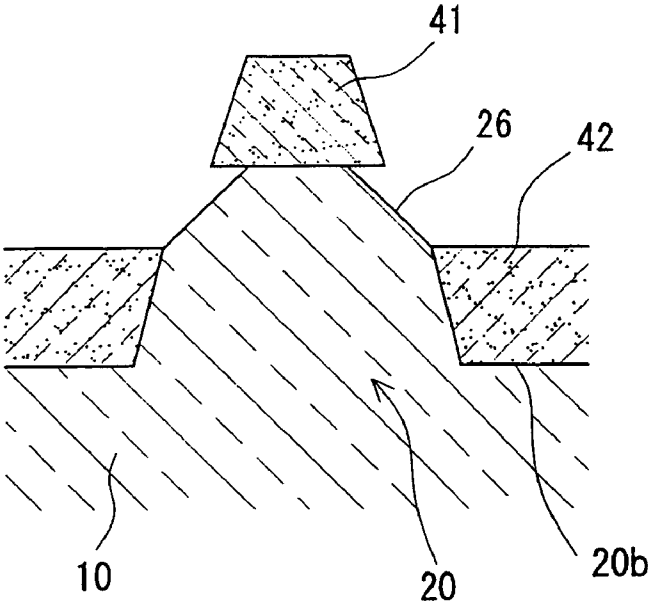


Fig. 17B

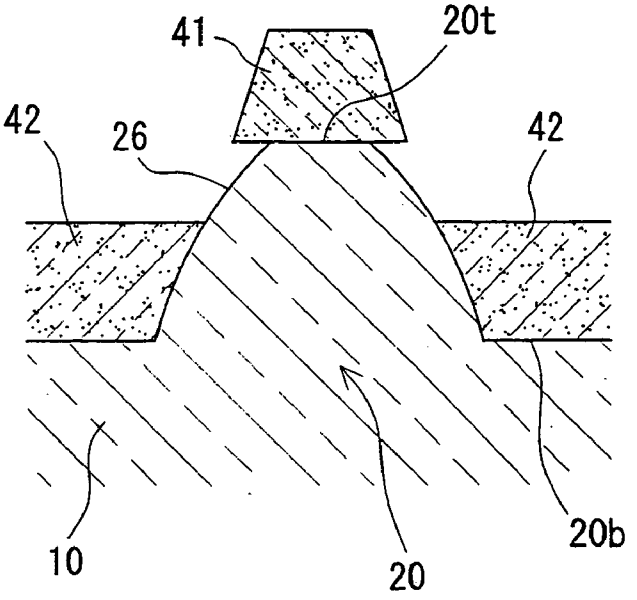


Fig. 18A

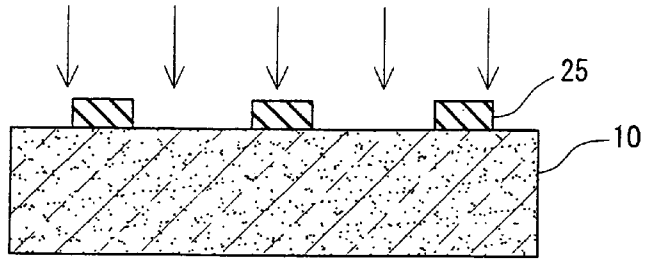


Fig. 18B

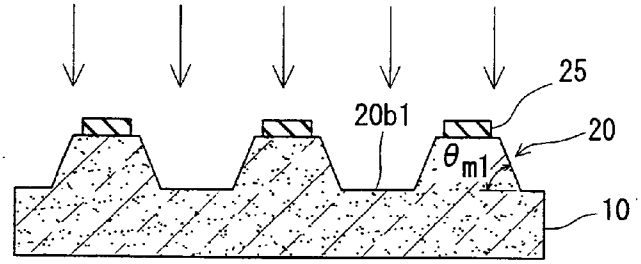


Fig. 18C

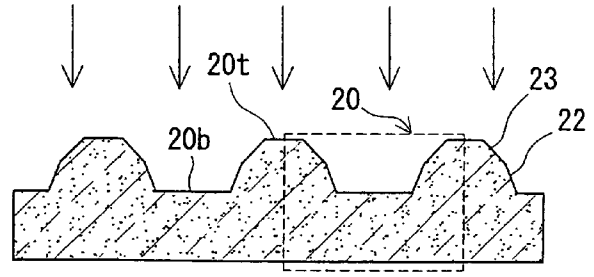


Fig. 18D

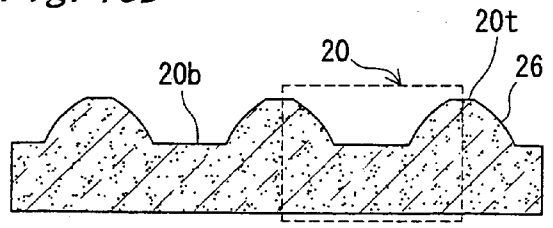


Fig. 18F

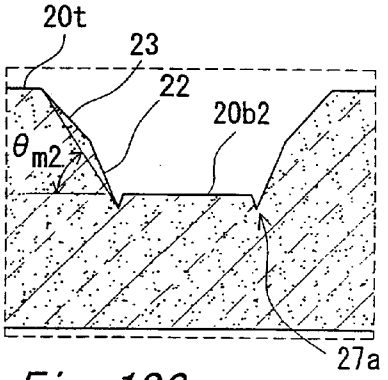


Fig. 18G

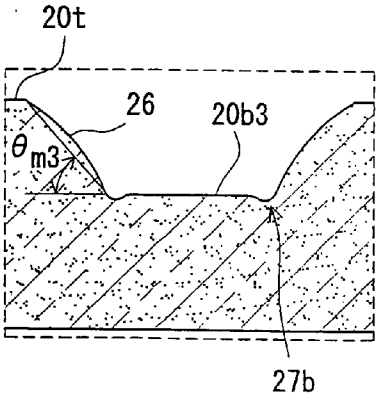


Fig. 19A

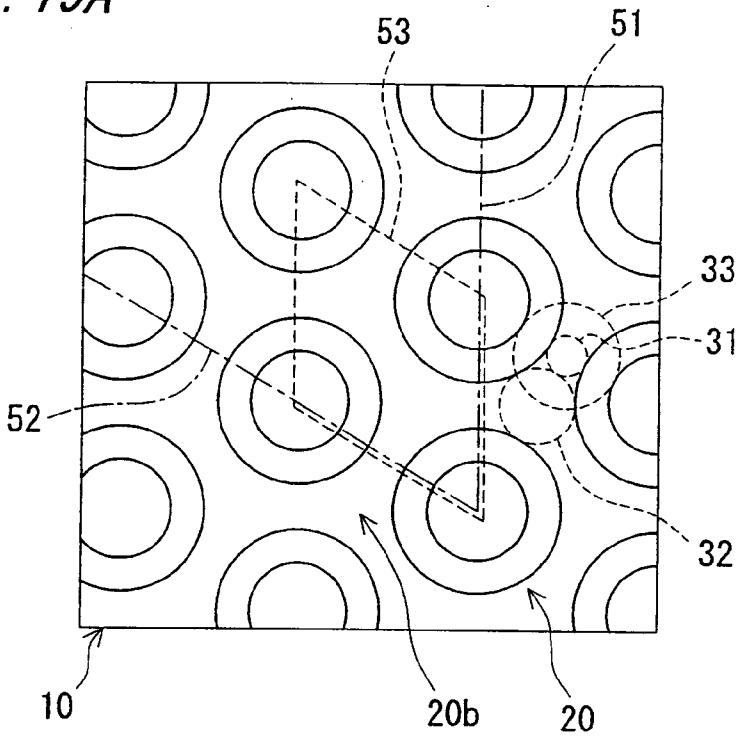


Fig. 19B

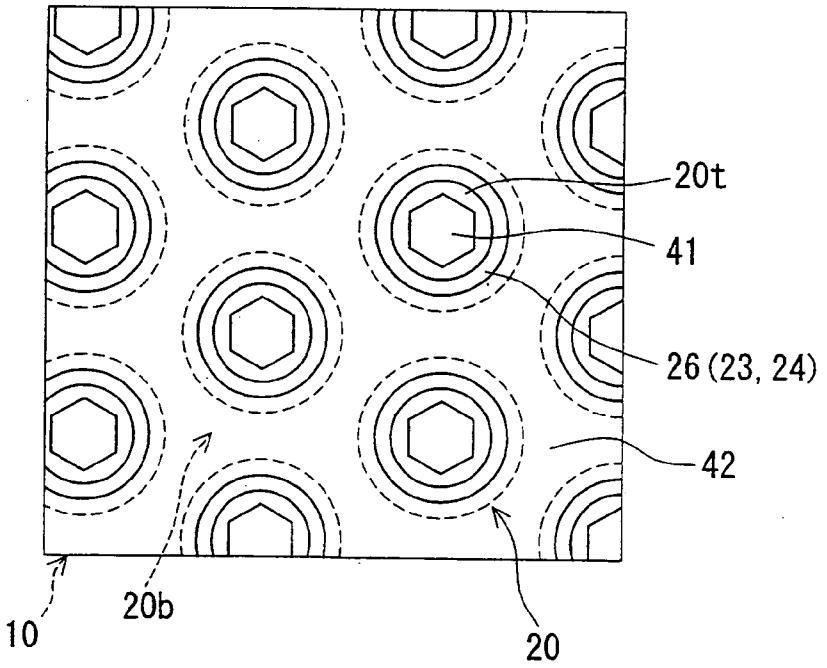


Fig. 19C

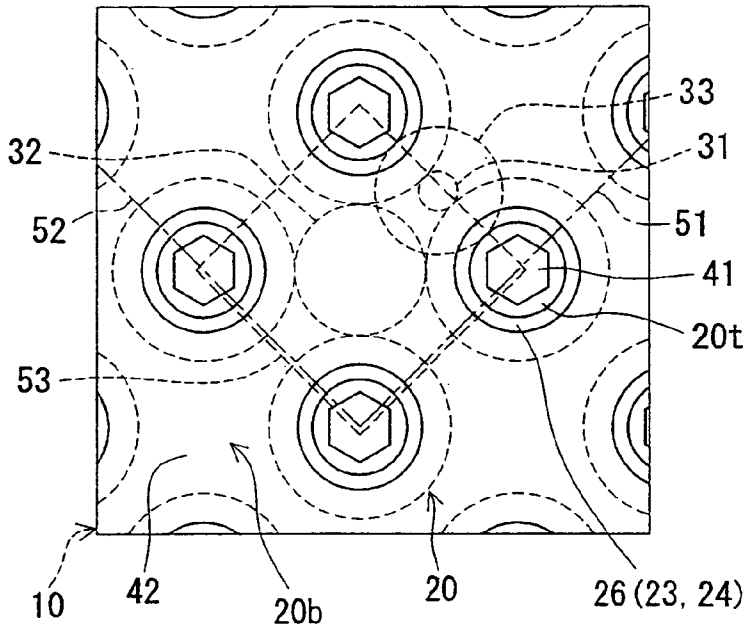


Fig. 19D

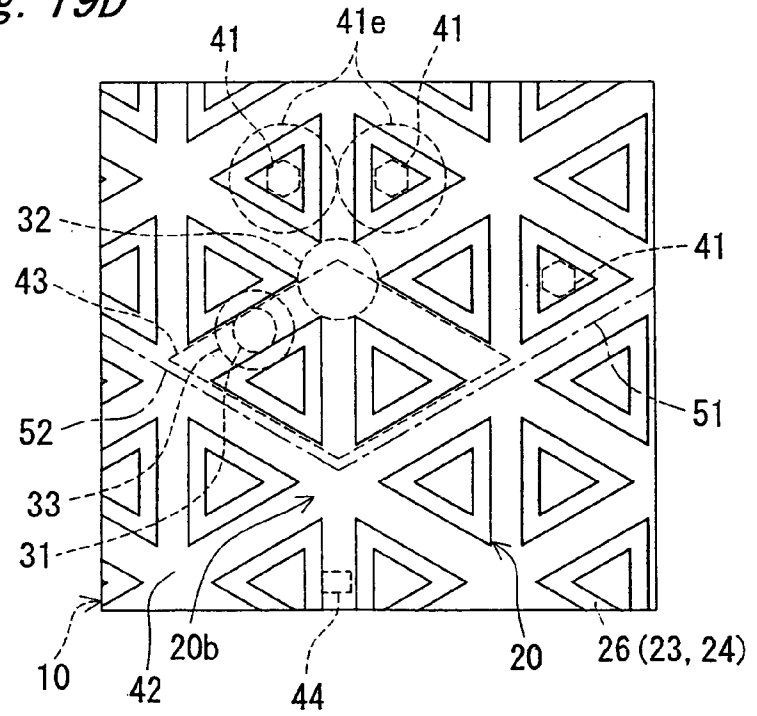


Fig. 20

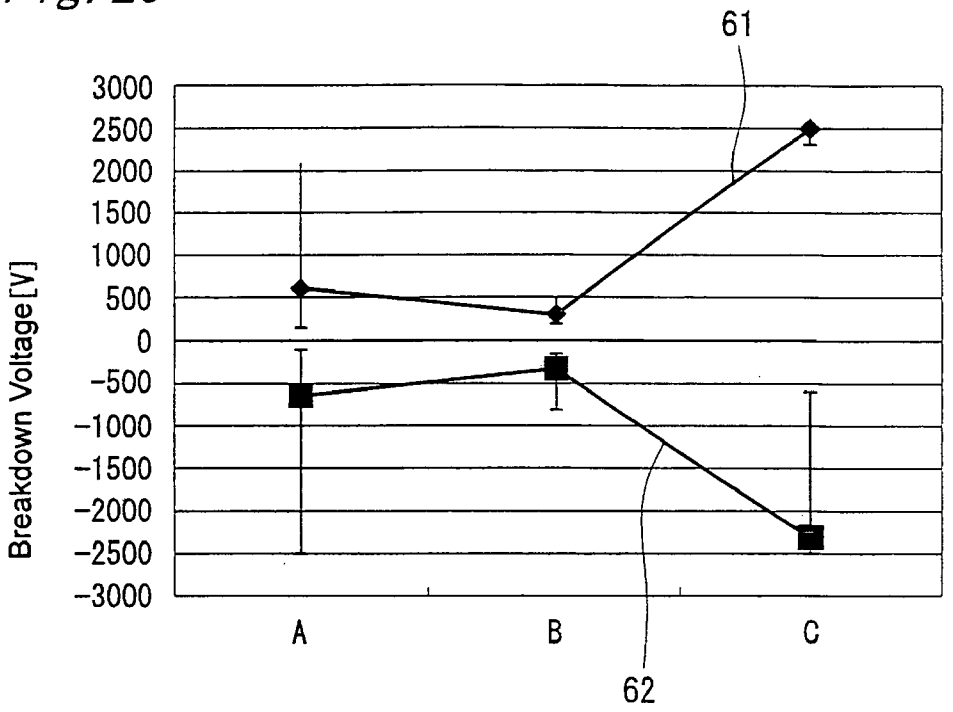

61
3000
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
Breakdown Voltage [V]
A
B
C
62

Fig. 21

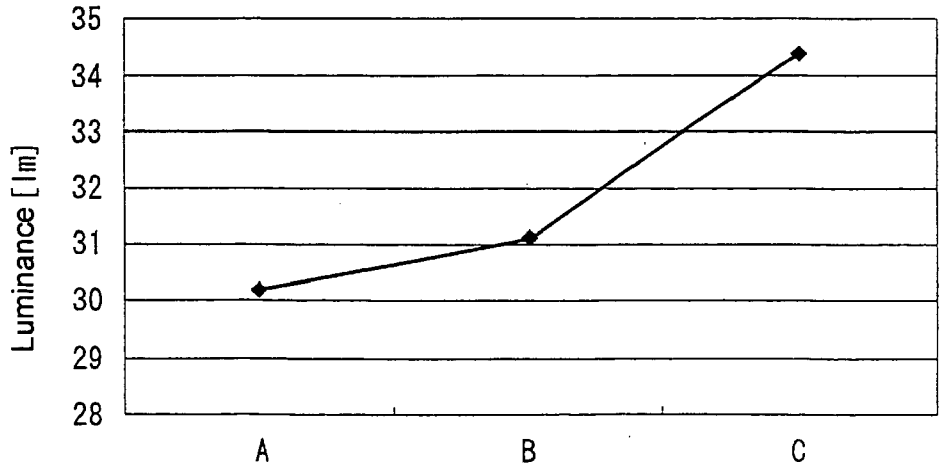

35
34
33
32
31
30
29
28
Luminance [lm]
A
B
C

Fig. 22A

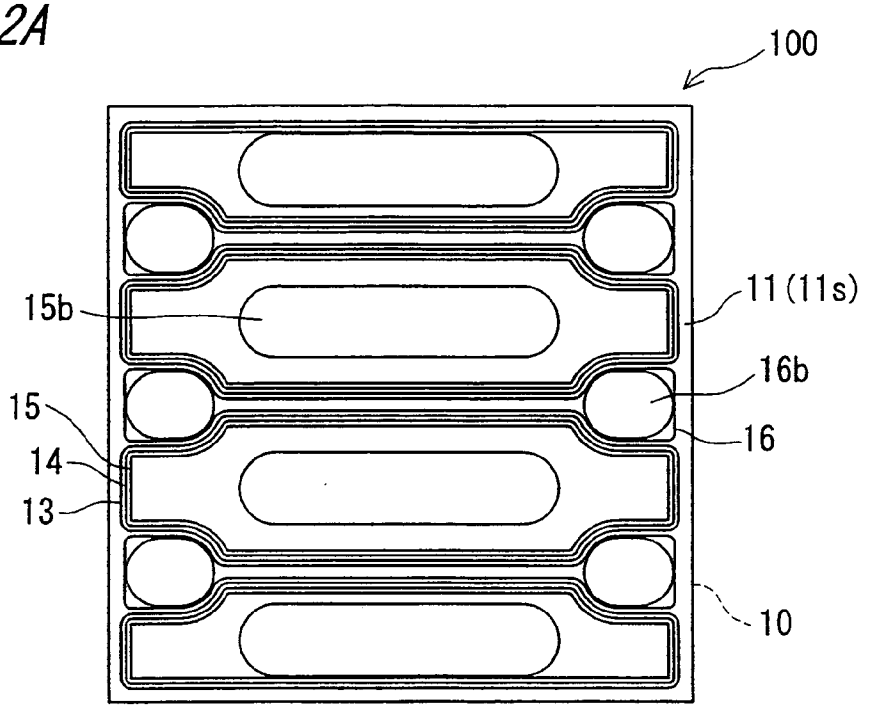


Fig. 22B

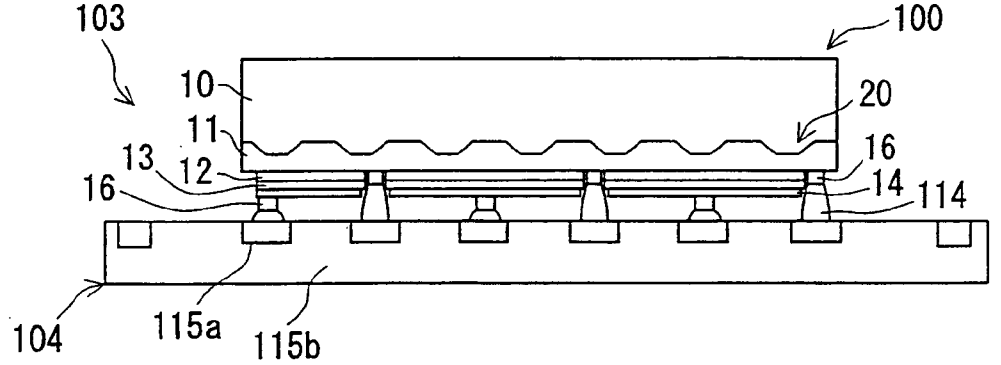


Fig. 22C

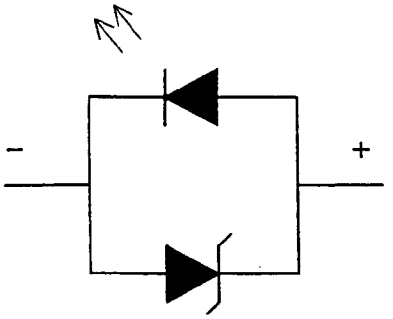


Fig. 23

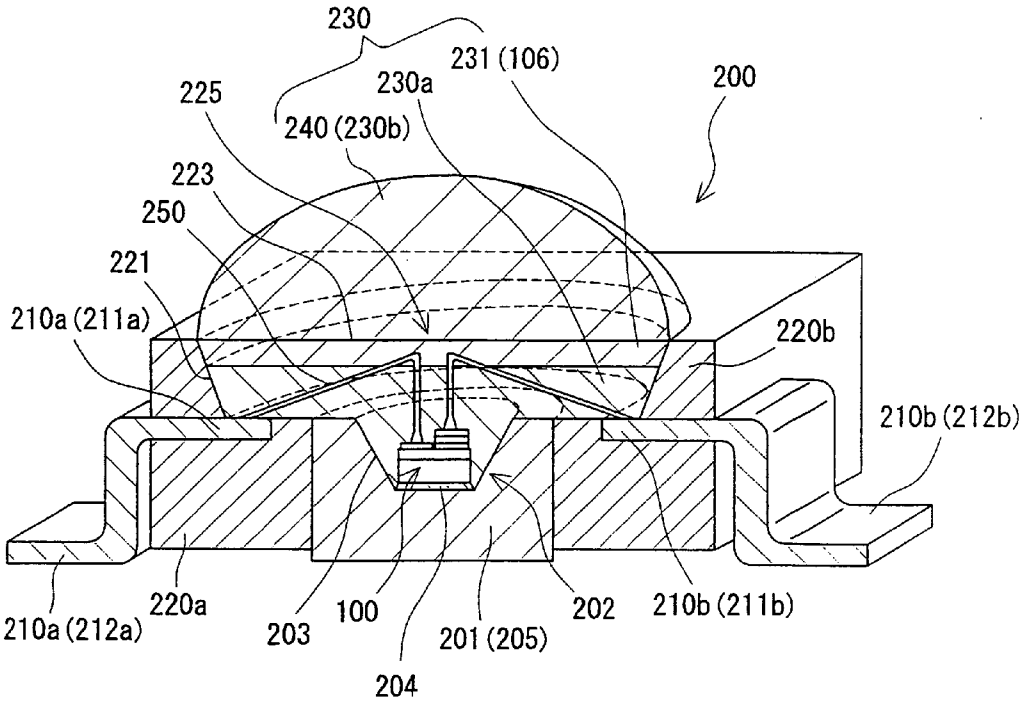

230
231 (106)
230a
225
240 (230b)
200
223
250
221
210a (211a)
220b
210b (212b)
210a (212a)
220a
203
100
202
210b (211b)
201 (205)
204

Fig. 24

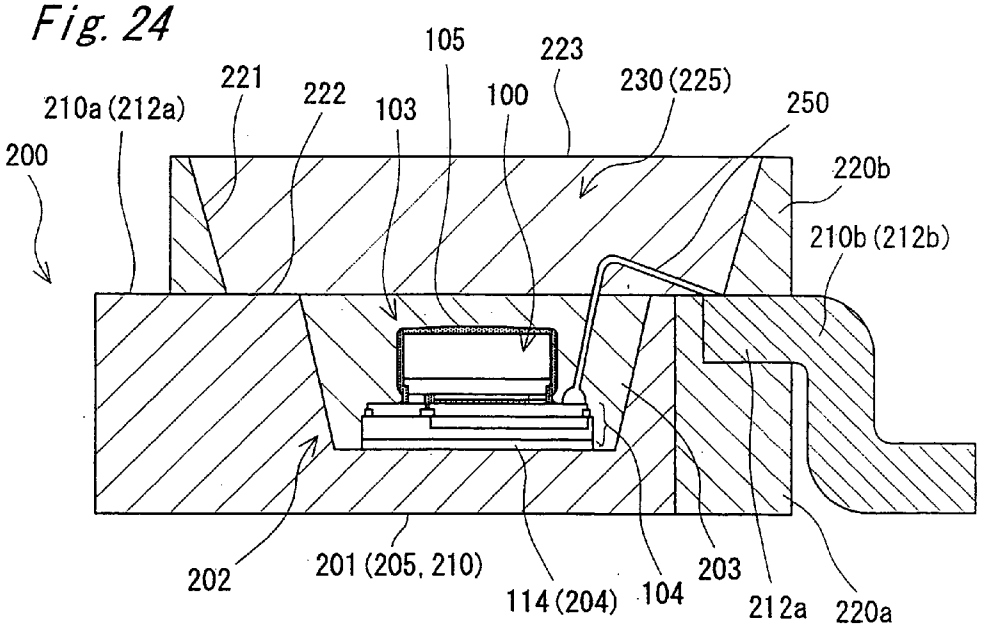

105
223
221
222
103
100
230 (225)
250
210a (212a)
200
220b
210b (212b)
202
201 (205, 210)
114 (204)
104
203
212a
220a

Fig. 25A

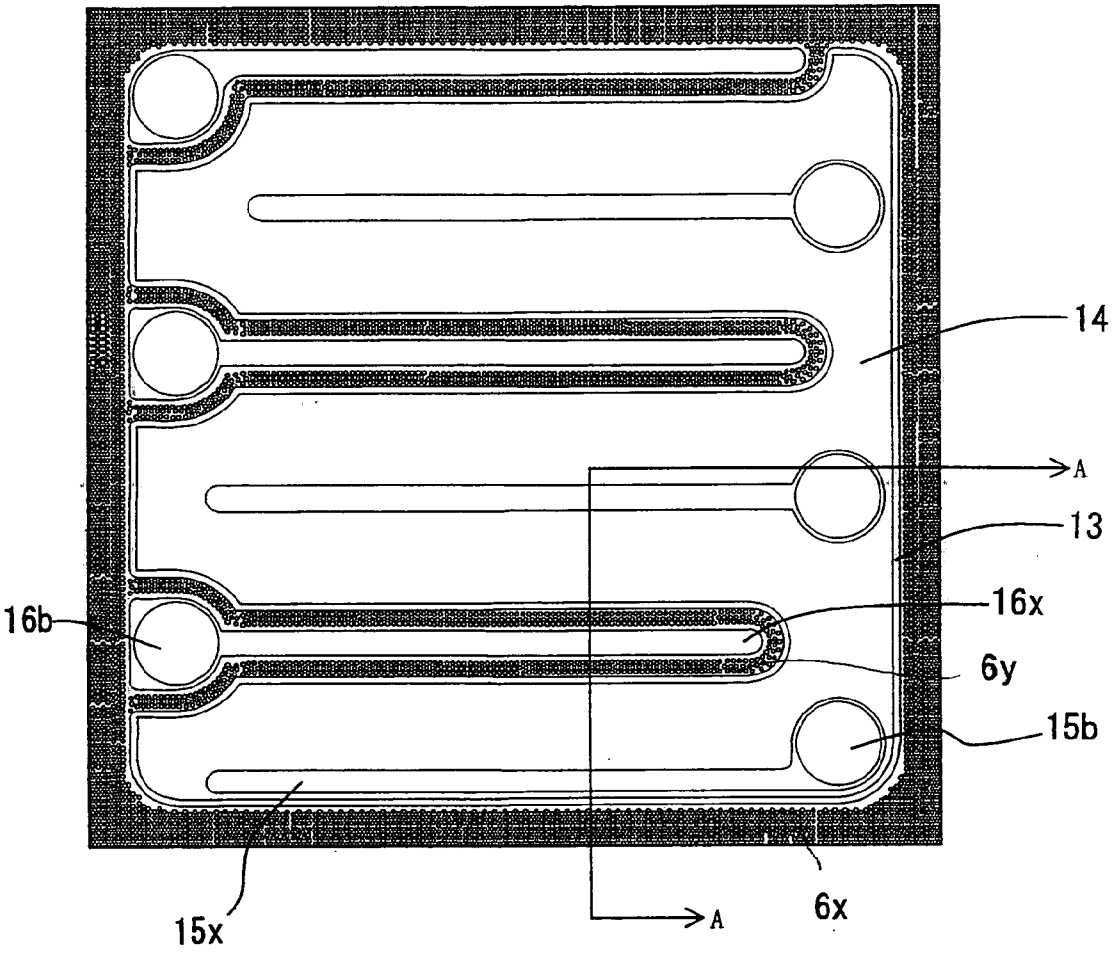
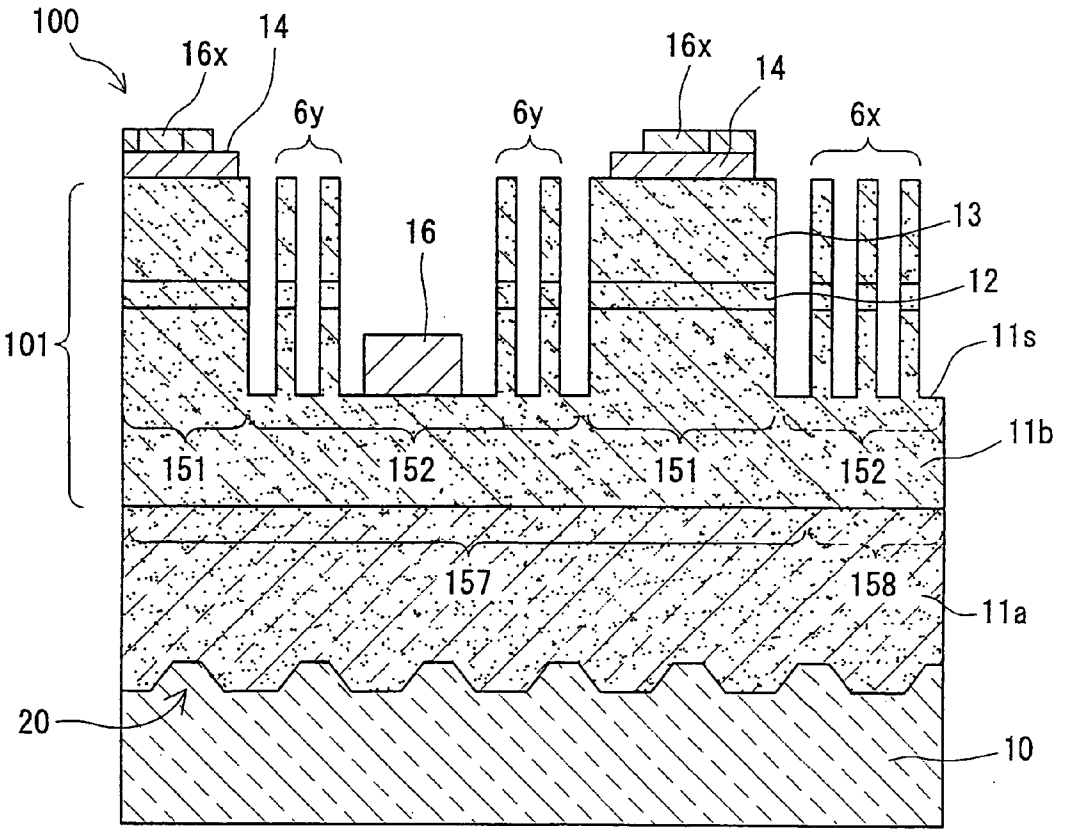


Fig. 25B


100
16x
14
6y
6y
16x
14
6x
16
13
12
101
11s
11b
151
152
151
152
157
158
11a
20
10

SEMICONDUCTOR DEVICE

TECHNICAL FIELD

[0001] The present invention relates to a semiconductor device having recess or protrusion provided on a substrate and, more particularly, to a semiconductor light emitting device that improves its external efficiency by having the recess or protrusion provided on the substrate.

BACKGROUND ART

[0002] A semiconductor device, for example, a light emitting diode (LED) essentially comprises an n-type semiconductor layer, an active layer and a p-type semiconductor layer laminated on a substrate in this order. Electrodes are formed on the p-type semiconductor layer and on the n-type semiconductor layer. Light is generated in a light emitting region of the active layer through recombination of holes injected from the p-type semiconductor layer and electrons injected from the n-type semiconductor layer. The light is extracted to the outside from the surface whereon the electrode is formed, or from the back surface of the substrate where semiconductor layer is not formed.

[0003] A light emitting diode having such a structure as described above requires it to control the laminated structure of semiconductor at atomic-layer level, and for this purpose, it is a common practice to process the substrate surface to mirror finish. The semiconductor layers and the electrodes are formed parallel to each other on the substrate, and a light-propagating portion is formed so that light propagates through the semiconductor portion. The light-propagating portion is formed so that a semiconductor layer having a high refractive index is sandwiched between the substrate and the electrode, both of which have lower refractive indices. The waveguide is interposed between the p-type semiconductor layer-electrode interface and the substrate-electrode interface.

[0004] When light generated in the semiconductor layer enters with an angle of incidence not smaller than the critical angle with respect to the interfaces with the electrodes or the interface with the substrate, the light laterally propagates while repeating total reflection within the semiconductor layer. As a result, light is trapped within the waveguide and cannot be extracted to the outside efficiently. In addition, part of light is absorbed while laterally propagating with repeating total reflection within the semiconductor layer, resulting in lower external quantum efficiency.

[0005] A method of roughing the top surface and side faces of the light emitting diode chip has been proposed, but it causes damage on the semiconductor layer and results in cracks and/or other trouble. This leads to partial breakage of p-n junction and reduction in effective light emitting region.

[0006] Japanese Unexamined Patent Publication (Kokai) No. 11-274568 proposes a method of increasing the external quantum efficiency by creating recess or protrusion on the surface of a substrate so that light generated in the light emitting region is scattered. This method employs a mechanical process or etching for randomly roughing the surface of a sapphire substrate of a GaN-based LED comprising the sapphire substrate, an n-type GaN layer, a p-type GaN layer and a transparent electrode that are laminated in this order. This process is supposed to scatter the light incident on the sapphire substrate so as to increase the external quantum efficiency.

SUMMARY OF THE INVENTION

[0007] However, when recess or protrusion having insufficient accuracy due to fine structure thereof is formed on the substrate surface without controlling the shape, the recess or protrusion may have significant notches formed on the side face thereof, resulting in rugged circumference (**FIG. 14**). A GaN layer grown on such a substrate surface is likely to have pits and/or voids, which in turn make it easier for cracks to occur during regrowth of GaN. This results in lower crystallinity of GaN which decreases the efficiency of light emission (internal quantum efficiency) and thus the external quantum efficiency decreases contrary to the intention. These cracks also lower the reliability of the semiconductor device. Influence of lowering crystallinity of the semiconductor is not limited to light emitting devices such as light emitting diode, but adversely affects other semiconductor devices of light sensor and electronic devices.

[0008] When recess or protrusion is formed on the substrate surface whereon a semiconductor is to be grown, the semiconductor may grow with anomaly that may result in various troubles. For example, such troubles may result as deterioration of surface morphology caused by pits formed in the semiconductor layer surface and the like; occurrence of void caused by insufficient semiconductor growth without filling the recess; threading dislocation and other crystalline defect caused in the semiconductor layer by defective growth of the semiconductor; or occurrence of a partial abnormal growth in the wafer surface. Undesirable surface morphology due to pit or other like formed in the surface or poor crystallinity due to crystal defects lead to increase in the electrostatic discharge damage due to leakage current or decreased efficiency of light emission due to subsequently deteriorated crystallinity of the active layer or the like, which may result in unsatisfactory properties of the semiconductor device. Voids caused by recess or protrusion may cause poor crystallinity and/or pit and may also hamper the optical effect of the recess or protrusion in the substrate. When a partial abnormal growth occurs in the wafer, lower yield of device production results.

[0009] In consideration of the problems described above, an object of the present invention is to provide a semiconductor device characterized by high reliability including electrostatic discharge tolerance, better crystallinity and high efficiency of light emission, by suppressing the generation of pits and voids in the semiconductor layer due to the formation of recess or protrusion on substrate surface. Another object of the present invention is to provide a semiconductor device that can be manufactured with a high yield of production which achieving stable external quantum efficiency, and a method of manufacturing the same.

[0010] The semiconductor device of the present invention comprises a substrate having recess and/or protrusion formed in the surface thereof and semiconductor layers formed, from materials different from that of the substrate, on the substrate surface, wherein the side face of the recess and/or protrusion includes at least two faces of different angles of inclination. The expression "include at least two faces of different angles of inclination" means that the side face of the recess and/or protrusion is constituted from two or more sloped surfaces of different angles of inclination with respect to the bottom of the recess and/or protrusion. **FIG. 5A** shows an example of cross section of the protru-

sion, in which case the side face of the protrusion includes two sloped surfaces having different angles of inclination θ_1 and θ_2. Number of sloped surfaces is not limited to two, but may be larger. That is, angles of inclination are not limited to θ_1 and θ_2, and n kinds of angles of inclination up to θ_n (n is an integer) may be provided.

[0011] The protrusion formed on the substrate surface preferably has convex side face (that swells toward the outside) as shown in **FIG. 5A** and **FIG. 15**. In case a recess is formed in the substrate surface, it is preferable that the inner surface of the recess protrudes toward the inside of the recess. This is because, for example in the case of a protrusion as shown in **FIG. 17A** and **FIG. 17B**, after the semiconductor layer has grown up to the apex of the side face of the protrusion, the semiconductor layer grown from the top of the protrusion and the layer grown from the valley between adjacent protrusions join in such a manner that decreases the inclination angle of the side face of the protrusion, so that the joint can be formed smoothly. This enables it to suppress the occurrence of abnormal crystal growth such as voids and pits and deterioration of crystallinity. The protruding (swelling) shape of the side face of the recess or the protrusion includes not only the beak-shaped protrusion such as shown in **FIG. 5A** but also convex curved surface as shown in **FIG. 15**. The protruding (swelling) shape of the side face refers to such a shape as illustrated by a sectional view of **FIG. 15** where the side face is on the outside of the straight line that connects the edge of the top face and the edge of the base (or, in the case of a recess, the side face is on the inside of the straight line that connects the edge of the surface that surrounds top opening and the edge of the bottom). In other words, in the case of protrusion, cross section of the protrusion is wider than a normal trapezoid. In the case of recess, cross section of the recess is narrower than a normal inverted trapezoid. According to the present invention, a plurality of protruding portions may be provided on the side face of the protrusion or recess. It is preferable, however, that the side face of the recess or protrusion has a single protruding portion as shown in **FIG. 5A** and **FIG. 15**, to ensure stable growth of semiconductor on the substrate.

[0012] As mentioned previously, the recesses or protrusions are preferably formed with high density in order to achieve a high efficiency of extracting light. That is, it is preferable to form small recesses or protrusions at small intervals. However, as the recesses or protrusions become smaller, it becomes difficult to form satisfactory recesses or protrusions due to the limitation of the machining accuracy, and notches are likely to be formed on the side face of the recesses or protrusions. In case the side face **21** of recess or protrusion has a constant angle of inclination as shown in **FIG. 4B** and **FIG. 4C**, notches **24** formed along the sloped side face **21** reach the top face **20** of the protrusion. This results in rugged circumference of the top face of the protrusion **20** as the notches cut into the circumference of the top face. Such notches are not formed regularly in the substrate surface, but are formed with irregular shapes and sizes. Therefore, occurrence of pits and voids cannot be suppressed simply by controlling the conditions of growing the semiconductor layers.

[0013] In contrast, two or more sloped surfaces **22**, **23** of different angles of inclination are formed on the side face of the recess and/or protrusion as shown in **FIG. 4A** according to the present invention. Thus the notches **24** generated in the lower sloped surface **22** are less likely to reach the top surface of the protrusion **20**. In other words, notches down the slope are formed only on the lower first sloped surface among the first and second sloped surfaces **22**, **23**. The notches extend to reach the boundary of the second sloped surface **23**, but do not extend into the second sloped surface. Consequently, the upper second sloped surface **23** is free from notches running along the slope, resulting in smaller roughness of the sloped surface. Abnormal morphology such as pits can be suppressed by growing semiconductor layer on the surface having such recess and/or protrusion. Forming the recess and/or protrusion on the substrate surface leads to no significant increase in dislocations formed in the semiconductor layer. This is supposedly because surface roughness of the upper sloped surface is made smaller than that of the lower sloped surface, and the circumference of the top surface of the protrusion is formed smoothly. The expression that "the circumference is formed smoothly" means that there are no substantial notches in the circumference.

[0014] In case the protrusion or recess has curved side face, it is supposed that the semiconductor growing from the valley between protrusions or from the bottom of a recess has smoother and smaller changes in the shape of the growing region, thus resulting in satisfactory growth. Notches formed on the side face of the recess or the protrusion can also be reduced by forming the protrusion or recess with curved side face.

[0015] It is preferable to form at least a first sloped surface and a second sloped surface, from the bottom of the substrate, on the side face of the protrusion with angle of inclination θ_1 of the first sloped surface with respect to the bottom of the recess and/or protrusion and angle of inclination θ_2 of the second sloped surface with respect to the bottom of the recess and/or protrusion satisfying the relation $\theta_1 > \theta_2$. Propagation of notches generated on the side face of the protrusion from the first sloped surface to the second sloped surface can be prevented by such a constitution of the sloped surfaces. It is preferable to make the first angle of inclination θ_1 larger since it decreases the depth and size of the notches formed in the first sloped surface. The same applied to a case where recess is formed.

[0016] It is preferable to form at least a first sloped surface **22** and a second sloped surface **23**, from the bottom of the substrate, on the side face of the protrusion with surface roughness Ra_1 of the first sloped surface **22** and surface roughness Ra_2 of the second sloped surface **23** satisfying the relation $Ra_1 > Ra_2$. Generation of voids and the like can be greatly reduced when growing the semiconductor by making the surface roughness Ra_2 of the second sloped surface smaller. It is supposed that generation of voids is suppressed because variations in the semiconductor growth rate between the protrusions are suppressed, and the junction between semiconductors is formed at constant point. In case the side face of the protrusion is formed from a single sloped surface as shown in **FIG. 14**, surface roughness Ra_3 of the side face becomes larger than the surface roughness Ra_1 or Ra_2 of at least one of the sloped surfaces in the case of forming two sloped surfaces as described above. Moreover, since the large surface roughness continues to the top surface of the protrusion, occurrence of voids cannot be avoided even when the conditions of growing the semiconductor is

controlled, thus resulting in lower output power. Surface roughness Ra_2 of the second sloped surface is preferably 0.1 μm or less, more preferably 0.01 μm or less and most preferably 0.005 μm or less.

[0017] As mentioned above, if notches formed on the side face of the recess and/or protrusion grow upward along the slope to the top surface of the recess and/or protrusion, crystallinity of the semiconductor to be grown in the subsequent process becomes lower. If notches formed on the first sloped surface do not grow into the second sloped surface, however, good crystallinity of the semiconductor can be achieved. This is because stress generated when growing the semiconductor is relaxed by the first sloped surface where the notches are generated, and generation of voids is suppressed by the second sloped surface where notches are not generated.

[0018] Either recess or protrusion may be formed on the substrate surface, and combination of recess and protrusion may also be formed. But it is preferable to form protrusions rather than recesses, since it makes it easier to grow the semiconductor layer without voids. When there are voids in the semiconductor layer around a recess or a protrusion, crystallinity of the semiconductor becomes lower and the function of recess or protrusion to scatter or diffract light is impeded, resulting in lower output power of the light emitting device. In order to prevent defects from growing in the semiconductor layer, it is preferable to make the second sloped surface provided on the side face of the recess and/or protrusion flat.

[0019] [Plan-View Shape of Protrusion (Recess)]

[0020] In order to prevent defects from developing in the semiconductor layer, it is preferable to make the second sloped surface in the side face of the recess and/or protrusion flat. It is also preferable that the recess and/or protrusion have such a shape that is constituted from straight line segments which cross a plane substantially parallel to the stable growth plane of the semiconductor layer, as viewed from above the recess and/or protrusion. The "straight line segments which cross a plane substantially parallel to the stable growth plane as viewed from above the substrate" means straight lines that are not parallel to the intersect of the substrate surface and the stable growth plane and is inclined from the line of intersection. The stable growth plane refers to the facet surfaces formed as relatively smooth surfaces during the growth of semiconductor on the substrate. The stable growth plane generally appears as a facet in the course of growth. In the case of gallium nitride semiconductor, for example, any plane (particularly M-plane) parallel to A-axis in the substrate surface is the stable growth plane. Therefore, it is preferable to form the recess or protrusion in polygonal shape constituted from sides (=straight line segments) that are not parallel to a plane parallel to A-axis, namely straight line segments that are not parallel to A-axis. This is because, when the recesses and/or protrusions are formed in a shape consisting of straight line segments that are substantially parallel to the stable growth plane of the semiconductor layer, crystal defects are likely to occur in the portion when growing the semiconductor layer. Crystal defects in the semiconductor layer decrease the internal quantum efficiency, and eventually decreases the external quantum efficiency. Here A-axis refers to the direction normal to the A plane. In case A-axis is inclined from the substrate surface, the angle from the projection of A-axis onto the substrate surface may be considered. Straight line that is not parallel to a plane parallel to A-axis refers to a straight line that is not parallel to A-axis or to the projection of A-axis onto the substrate surface. A plane that is parallel to a plane parallel to A-axis refers to a plane of which intersect with the substrate surface is a straight line that is parallel to A-axis or to the projection of A-axis onto the substrate surface.

[0021] Configuration in plan view of the recess and/or protrusion viewed from above the substrate may be circle, triangle, parallelogram, hexagon or the like. Occurrence of pits and other defects can be suppressed by forming the recess or protrusion in polygons such as triangle, parallelogram or hexagon. More preferably, the recess or protrusion are formed in equilateral triangle, rhombus or equilateral hexagon. Occurrence of pits can be significantly suppressed and the second sloped surface can be easily formed when the recess or protrusion are formed in circles. It also makes it possible to increase the density of protrusions, namely increase the number of protrusions in a unit area, and increase the length and surface area of the side face, thereby increasing the effect of the protrusion to extract light and increasing the output power when it is used as a light emitting element.

[0022] In this specification of patent application, to form the recess or protrusion in polygon or circle means that they have polygonal or circular shape when viewed from above the substrate. When the recess or protrusion is formed to have polygonal shape in plan view, the shape may not be exact polygon in geometrical meaning, and may be rounded at edges for the reason of manufacturing process.

[0023] The recesses and/or protrusions are preferably formed in a repetitive pattern of the same shape, such as the pattern of a plurality of protrusions shown in **FIG. 7**. While a single recess or protrusion may serve the purpose, the efficiency to scatter or diffract light can be improved and external quantum efficiency can be improved further by forming the recess and/or protrusion in a repetitive pattern. Even when the recess and/or protrusion are formed in a repetitive pattern, occurrence of crystal defects due to the recess or protrusion can be suppressed by having at least the first and second sloped surfaces, more preferably by having a swelled side faces, further preferably by having curved and swelled side faces of protrusions or recesses, so entire surface of the substrate can be used as the light emitting surface.

[0024] [Size and Spacing of Recesses/Protrusions]

[0025] Depth of the recess or height of the protrusion is preferably 100 Å or more, and more preferably in a range from 1000 to 10000 Å. With the wavelength of emitted light (206 nm to 632 nm in the case of a light emission layer made of AlGaInN-based material) denoted as λ, sufficient scattering or diffraction of light cannot be achieved unless the depth or height is at least λ/4 or larger. Specifically, since light propagates within the semiconductor layer on the substrate as described above, the depth or height is preferably λ/4n or larger, where n is the refractive index of the medium of propagation. On the other hand, if depth of the recess or height of the protrusion goes beyond the range, it becomes necessary to increase the thickness of the semiconductor layer, namely the underneath layer for the struc-

ture of element, required for depositing over the recesses or protrusions to form a flat surface. When the laminated structure is formed without forming a flat surface over the recesses or protrusions of the substrate, it becomes difficult for current to flow along the layer, resulting in lower efficiency of light emission.

[0026] Size of the recess and/or protrusion viewed from above the substrate, or length La of one of the sides that constitute the base of the recess and/or the protrusion, is preferably at least $\lambda/4$ or larger, where λ is the wavelength of light emitted in the semiconductor (370 nm to 460 nm). When size of the recess and/or the protrusion is smaller than $\lambda/4$, sufficient scattering or diffraction of light cannot be achieved. Here, $\lambda/4$ translates into $\lambda/4n$, where n is the refractive index of the semiconductor layer that serves as the medium of propagation for the emitted light. Length L_b of one of the sides that constitute the top face of the recess and/or the protrusion is preferably 1.5 μm or larger. Forming the recess or the protrusion in such a size makes it possible to suppress the occurrence of voids coming up with semiconductor growth. It is more preferable to set the ratio L_t/L_b of length (L_b) of bottom of the recess and/or protrusion to length (L_t) of top surface of the recess and/or protrusion in a range of $1<L_t/L_b<2$, and more preferably $1.1<L_t/L_b<1.8$. This constitution makes it possible to suppress the occurrence of voids more effectively and increase the output power by as much as 10% or more.

[0027] In order to achieve sufficient scattering or diffraction of light, distance between the recesses or between the protrusions as viewed from above the substrate is preferably $\lambda/4$ or larger, similarly to that described above. For example, distance between the recesses or between the protrusions is preferably in a range from 0.5 μm to 5 μm inclusive, and more preferably from 1 μm to 3 μm inclusive. When the distance is within such a range, the semiconductor layer can be grown efficiently and, consequently, the efficiency of scattering or diffraction can be improved. The distance between the recesses or between the protrusions refers to the minimum distance between adjacent recesses or protrusions.

[0028] [Sectional Shape of Recess/Protrusion]

[0029] Cross sectional shape of the recess or protrusion is preferably trapezoid having side face that consists of two or more faces of different angles of inclination in the case of protrusion as shown in **FIG. 5A**, or a trapezoid having a curved side face that consists of first and second angles of inclination θ_1 and η_2 as shown in **FIG. 15**. In the case of recess, it preferably has a shape of inverted trapezoid having a side face similar to that described above. Such a cross sectional shape makes it possible to further improve the efficiency of scattering or diffraction of light. The cross sectional shape of the recess or protrusion may not be exact trapezoid or inverted trapezoid in geometrical meaning, and may be rounded at edges for the reason of manufacturing process.

[0030] In case at least the first sloped surface and the second sloped surface, in this order from the bottom of the substrate, are formed on the side face of the protrusion with angle of inclination θ_1 of the first sloped surface with respect to the bottom of the recess and/or protrusion and angle of inclination θ_2 of the second sloped surface with respect to the bottom of the recess and/or protrusion, output power due to scattering or diffraction is improved when angle of inclination θ_1 is larger than 30° and smaller than 90°. When the angle of inclination θ of the recess or protrusion is too large, the efficiency of scattering or diffraction decreases contrary to expectation, and pits are more likely to occur in the semiconductor layer. Thus angle of inclination θ_1 is preferably in a range from 45° to 80° inclusive, and preferably in a range from 50° to 70° inclusive. Angle of inclination θ_2 is preferably in a range from 10° to 30° inclusive. Forming the recess or protrusion with angles in such ranges on the substrate surface enables it to suppress the occurrence of pits. Angle of inclination θ_3 of the second sloped surface with respect to the top surface of the recess and/or protrusion is preferably 90° or larger.

[0031] In case the protrusion has a convex side face so that the width of the cross section increases at the middle as shown in **FIG. 5A** or **FIG. 15**, it is preferable that the inclination angle θ_m between the line connecting the edge of the bottom and the edge of the top face of the protrusion and the bottom plane of the protrusion is within a range from 20 to 80°, more preferably from 30 to 60°, as shown in **FIG. 15**. If the inclination angle is too large, light reflecting surface (side face of the protrusion) occupies a smaller proportion of substrate surface, resulting in lower effect of extracting light. If the inclination angle is too small as shown in **FIG. 17A, 17B**, the semiconductor grown from the valley between adjacent protrusions join with the semiconductor grown from the top of the protrusion in such a manner as the former creeps below the latter in larger area, leading to the occurrence of defective growth and/or voids. In the case of recess, the supplement of the inclination angle θ_m between the line connecting the edge of the bottom and the edge of the top face of the recess and the bottom plane of the recess is preferably within the range described above.

[0032] [Types of Substrate and Semiconductor]

[0033] According to the present invention, there are no limitations to the kinds of materials used to make the substrate and semiconductor. The semiconductor formed on the substrate surface may be a semiconductor based on group III-V element or a semiconductor based on group II-VI element. Semiconductors based on group III-V elements include nitride semiconductors, among which GaN-based semiconductor, in particular, is preferably used. The stable growth plane of GaN-based semiconductor is generally M-plane {1-100} of hexagonal crystal system. The notation {1-100} represents all of (1-100), (01-10), (−1010), etc. M-plane is one of the planes that are parallel to A-axis in the substrate surface. Other planes that include A-axis of GaN semiconductor in the substrate surface, namely planes other than M-plane, such as the facet of {1-101} plane may also become the stable growth plane, depending on the growing condition.

[0034] As for the substrate, a sapphire substrate, a Si substrate, a SiC substrate or a spinel substrate can be used. For example, a sapphire substrate having a C plane (0001) as the principal plane can be used. In this case, the M-plane that is the stable growth plane of GaN-based semiconductor layer is the plane parallel to A plane {11-20} of the sapphire substrate. The A plane {11-20} represents all of (11-20), (1-210), (−2110), etc.

[0035] When nitride semiconductor is grown on C plane of a sapphire substrate, for example, crystal growth begins at hexagonal spots enclosed by planes that include A-axis of

the nitride semiconductor, like islands, and the islands eventually join with each other to form a homogeneous semiconductor layer. Therefore, it is preferable to form the recess or protrusion in such a planar configuration as a polygon (triangle, hexagon, etc.) that is constituted from sides which are perpendicular to straight lines connecting the center and vertices of an equilateral hexagon that is defined by A-axis of the nitride semiconductor as its sides. Side face of the recess and/or the protrusion is formed so as to comprise at least two sloped surfaces, in a protruding shape having two or more inclination angles or in a convex curved surface. The sapphire substrate having the recess or protrusion formed thereon allows it to grow nitride semiconductor having flat surface and high crystallinity on the surface thereof.

[0036] [Structure of Light Emitting Device Having Substrate with Recess/Protrusion]

[0037] The present invention, when applied to a semiconductor light emitting device, can provide a light emitting device having high efficiency of extracting light. In this case, while an ohmic electrode **14** formed on the light extracting surface of the semiconductor light emitting device may be formed on substantially the entire surface of the semiconductor layer **13** as shown in **FIG. 8A** and **FIG. 8B**, it is preferable to form the ohmic electrode in such a shape that has through holes **18**. When a semiconductor layer is formed on the substrate having the recess or protrusion formed thereon and the electrode having the holes are formed thereon over the entire surface, the efficiency of extracting light is greatly improved by the mutually enhancing effects of both features.

[0038] The reason for the above is as described below. When a transparent electrode is formed over the entire surface of the semiconductor layer, part of the light directed upward through scattering or diffraction by the recess or protrusion on the substrate surface is absorbed by the transparent electrode, resulting in lower intensity of the optical output. When an opening is formed in a transparent electrode, or an opening is formed in an opaque electrode having high reflectivity, light directed upward through scattering or diffraction can be extracted to the outside efficiently without being absorbed by the electrode, resulting in improved efficiency of extracting light. It is preferable that at least one recess or protrusion, that is formed on the substrate surface, is included in the opening **18** of the electrode.

[0039] In the case of a semiconductor device that employs nitride semiconductor, the ohmic electrode formed on the p-type semiconductor may be made of an alloy that includes at least one kind selected from among a group consisting of Ni, Pd, Co, Fe, Ti, Cu, Rh, Ir, Au, Ru, V, W, Zr, Mo, Ta, Pt, Ag, oxide or nitride of these elements. Electrically conductive metal oxides (oxide semiconductors) such as indium tin oxide (ITO), ZnO, In_2O_3 and SnO_2 may also be used. Moreover, an alloy layer or a multi-layer film that includes one of the above can also be used. The translucent electrode is preferably made of ITO film in the visible light region. The reflective electrode is preferably made of Al, Ag or Rh for improving the efficiency of extracting light and other reason.

[0040] The semiconductor device of the present invention has an effect of improving the crystallinity of the light emitting region (active layer) and increasing the output power by forming the recess or protrusion that scatters or diffracts light in the interface between the semiconductor layer and the substrate instead of the interface between the semiconductor layer and the electrode. According to the present invention, light is scattered or diffracted by the recess and/or protrusion and is extracted efficiently upward from the semiconductor layer or downward from the substrate, resulting in greatly improved external quantum efficiency, in contrast to a flat substrate of the prior art in which light is transmitted laterally. According to the present invention, first, intensity of light directed upward or downward from the substrate is increased by scattering or diffraction by the recess or protrusion, and accordingly luminance of the light emission surface of the light emitting device viewed squarely in front thereof (front brightness) is increased. Second, light transmitted along the semiconductor layer is decreased by the effect of scattering or diffraction by the recess or protrusion, thereby reducing the absorption loss due to the transmission, and increasing the optical output.

[0041] In addition, according to the present invention, the recesses and/or protrusions are formed to have a side face comprising two or more sloped surfaces, preferably with protruding curved surfaces on the substrate surface, so as to suppress the formation of notches on the side face of the recess and/or the protrusion (**FIG. 12**, **FIG. 13**). As a result, the space surrounding the recess or protrusion can be completely filled with the semiconductor layer without causing voids. Thus high external quantum efficiency is achieved and high output power can be maintained stably. When the recess or the protrusion is formed in a circular shape, occurrence of pits can be greatly reduced. This improves the yield of production.

[0042] [Method of Manufacturing Substrate with Recess/Protrusion]

[0043] Method of manufacturing the substrate used in the light emitting device will be described below. While protrusions are formed in the example described below, the same method can be applied to a case of forming recesses.

[0044] First, an example shown in **FIGS. 2A through 2D** will be described. In this example, the protrusions are formed by etching in two steps. As shown in **FIGS. 2A and 2B**, a protective film **25** of a specified shape is formed as an etching mask on the substrate. Then as shown in **FIG. 2C**, the substrate is etched so as to form projections **20** (first step). Then as shown in **FIG. 2D**, after removing the protective film **25** as a whole, the substrate is etched further so as to form the protrusions **20** having two sloped surfaces (second step).

[0045] Now an example shown in **FIGS. 18A through 18D** will be described. In this example, the protrusions are formed by etching in three steps. As shown in **FIG. 18A**, the protective film **25** of a specified shape is formed as an etching mask on the substrate. Then the substrate is etched so as to form the projections **20** as shown in **FIG. 18B** (first step). In the first step, a part of the protective film **25** is etched to reduce the area thereof. Then the substrate is etched so as to form the protrusions **20** having two sloped surfaces while leaving the protective film remain or after removing the protective film as a whole (second step). In the second step, etching is carried out by exposing at least part

or whole of the top face **20***t* of the protrusion, the side face of the protrusion and the portion between the protrusions (in other words, recess).

[**0046**] As can be seen from **FIG. 18C** (or **FIG. 2D**), the inclination angle θ_{m1} of the sloped surface of the protrusion **20** formed in the first step is larger than the inclination angle θ_{m2} of the sloped surface of the protrusion **20** as a whole formed in the second step ($\theta_{m1}>\theta_{m2}$). Here, the inclination angle θ_{m2} of the sloped surface of the protrusion **20** as a whole formed in the second step means the inclination angle between the line connecting the edge of the bottom and the edge of the top face of the protrusion and the bottom face of the protrusion.

[**0047**] **FIG. 18E** shows a partially enlarged view of boxed part by dotted line in **FIG. 18C**. As shown in **FIG. 18E**, after the second step, there may be a case where relatively sharp V-shaped notch **27***a* is formed at the edge of the first sloped surface **22** of the larger inclination angle on the base, namely on the periphery of the valley **20***b*$_2$ between the protrusions (periphery of bottom **20***b*$_2$ of the recess, in the case of recess). This is because notch is formed to extend along the first sloped surface **22** and the first sloped surface **22** has greater inclination angle than the second sloped surface **23**, and therefore the joint of the first sloped surface **22** and the flat surface **20***b***2** of the substrate is etched with preference.

[**0048**] Then as shown in **FIG. 18D**, in order to integrate the two side faces **22** and **23** of the protrusion into a single smooth and convex curved surface **26**, etching is carried out while exposing at least part or whole of the top face **20**t of the protrusion, the side face of the protrusion and the portion between the protrusions (in other words, recess) (third step). This results in the formation of smooth curved side face **26** of the protrusion **20** as shown in **FIG. 18D**. The curved surface **26** has the first inclination angle θ_1 on the bottom face side and the second inclination angle θ_2 on the top face side. **FIG. 18F** shows a partially enlarged view of boxed part by dotted line in **FIG. 18D**. As described above, there may be a case where notch **27***a* is formed on the periphery of the valley **20***b*$_2$ between the protrusions **20** in the second step. The notch **27***a* may lead to abnormal growth of the semiconductor. After the third step, however, the notch **27***a* is smoothed into smooth notch **27***b* as shown in **FIG. 18F**. Thus the abnormal growth of the semiconductor is suppressed.

[**0049**] In the third step, etching is carried out while exposing a part of the top face **20***t* of the protrusion, the side face of the protrusion and the portion between the protrusions after at least the first and second sloped surfaces **22**, **23** have been formed on the side face of the protrusion **20**, so as to form the side face of the protrusion **20** in a convex surface **26**. At this time, the side face **26** of the protrusion **20** is preferably formed in such a configuration as the inclination angle θ_2 on the top face side is smaller than the inclination angle θ_1 on the bottom side ($\theta_1>\theta_2$). Also it is preferable to make the inclination angle θ_{m3} of the entire side face of the protrusion **20** smaller than the inclination angle θ_{m2} of the sloped surface of the protrusion **20** formed after the second step ($\theta_{m2}>\theta_{m3}$), as shown in **FIG. 18E** and **FIG. 18F**. Making the inclination angle θ_{m3} smaller is advantageous for making the notch **27***a* smoother.

[**0050**] The inclination angle θ_m of the entire side face of the protrusion **20** can be made progressively smaller ($\theta_{m1}>\theta_{m2}>\theta_{m3}$) through the three etching steps of the first through third steps as described above. In the side face of the protrusion thus obtained, the inclination angle θ_2 on the top face side becomes smaller than the inclination angle θ_1 on the bottom side. These are preferable because the side face of the protrusion having such a configuration further suppresses the occurrence of voids, crystalline defects and surface pits in the semiconductor crystal that is grown over the protrusions, and provides better properties of the semiconductor device.

[**0051**] While the above description has dealt with inclination angle θ of the side face of the protrusion **20**, the discussion may also be based on the ratio of length L_t of the top face of the protrusion and the length L_b of the bottom of the protrusion. Ratio of bottom length to the length of top face (L_{b1}/L_{t1}) in the first process is preferably smaller than the ratio of lengths in the second process (L_{b2}/L_{t2}) ((L_{b1}/L_{t1})<(L_{b2}/L_{t2})). Similarly, relationship ((L_{b2}/L_{t2})<(L_{b3}/L_{t3})) preferably holds between the second step and the third step. This results in lager spacing between the top faces of the protrusions, so as to allow the satisfactory crystal growth of the semiconductor in the space between the protrusions, resulting in the better crystal growth of the semiconductor.

[**0052**] The multi-step etching process described above achieves smooth side face of the recess or protrusion. In the first step, rough side face **22***a* having notches formed thereon is likely to be formed because of the accuracies of etching and masking (**FIG. 4B**, **FIG. 4C**). The subsequent second step and third step of etching are carried out with at least a part of the top face **20***t* of the protrusion exposed, and therefore the notches **24** formed on the side face of the protrusion are smoothed. For example, in the second step, edge of the top face **20***t* of the protrusion **20** and corners of the notch **24** formed on the side face of the protrusion **20** are etched with preference. As a result, sharp edges are rounded as if chamfered. Thus as shown in **FIG. 4A** and **FIG. 5A**, the second sloped surface **23** is formed on the side face of the protrusion **20** and, at the same time, the first sloped surface **22** is smoothed. At this time, as shown in **FIG. 2D** and **FIG. 18F**, the inclination angle Em of the entire side face of the protrusion also decreases. Further in the third step, angular joint between the first sloped surface **22** and the second sloped surface **23** is rounded, and the notch **27***a* formed on the periphery of the base of the protrusion **20** in the second step is smoothed.

[**0053**] While the example described above dealt with a case where the protective film **25** is removed in the first step or the second step, timing of removing the protective film **25** can be selected as required. It is preferable to remove the protective film **25** simultaneously during the etching process to form the protrusion, since it eliminates the separate process of removing the protective film. In case the protective film **25** is left to remain in the first step, the remaining protective film **25** makes it easier to form the second sloped surface in the second etching step. The protective film **25** left to remain in the first step can also protect the top face **20***t* of the protrusion during the second step. Further in the second step, the protective film **25** may be left to remain so as to be removed in the third etching step. The protective film may further be left to remain in the third step. In the first to third step, the protective film may also be left in a shape that is

suitable for the respective step in order to obtain a desired shape of protrusion or recess (particularly the side face shape).

[0054] The side face of the protrusion **20** is formed preferably in a shape protruding (swelling) toward the outside as shown in **FIGS. 2D, 4A, 5A, 15** and **18C**. For example, the side face of the protrusion **20** is formed from the first sloped surface **22** on the bottom side and the second sloped surface **23** on the top face side. More preferably, such a side face **26** is formed that consists of the first sloped surface **22** and the second sloped surface **23** which are connected smoothly as shown in **FIG. 18D**.

[0055] In the manufacturing method described above, the plan-view configuration of the protrusion **20** may be selected as required, such as triangle, polygon, circle or the like. In case the plan-view configuration of the protrusion **20** has sharp corner, significant change in the shape can be caused during the multi-step etching operation, leading to significant variability in shapes of the protrusions among wafers or within a wafer, resulting in lower yield of production. The plan-view configuration of the protrusion **20** having sharp corner has disadvantage also with respect to crystal growth. That is, the nitride semiconductor grown on the top face **20***t* of the protrusion of the substrate has hexagonal crystal structure. In case the plan-view configuration of the protrusion is triangle as shown in **FIG. 19D**, gap is produced between the hexagonal semiconductor crystal and the triangular top face of the protrusion, thus making the semiconductor crystal likely to grow unevenly. Uneven growth of the semiconductor crystal increases the chance of abnormal growth such as pits when islands of semiconductor crystal join with each other to form a layer. In case the plan-view configuration of the protrusion is circle as shown in **FIGS. 19A through 19C**, on the other hand, gap between the hexagonal semiconductor crystal and the edge of the top face of the protrusion becomes smaller, thus making segregation of the semiconductor crystal less likely to occur. As a result, the semiconductor can be grown with abnormal growth such as pits being suppressed. Therefore, it is preferable that the plan-view configuration of the protrusion **20** (particularly the top face) does not have sharp corners. The shape is, for example, a polygon having vertices of right angles or obtuse angle (for example, polygon having four or more vertices), preferably a polygon having rounded vertices, more preferably ellipse, and most preferably circle.

[0056] [Arrangement of Recesses/Protrusions]

[0057] **FIGS. 19A through 19D** show examples of arrangement of protrusions. The arrangement of the protrusions is preferably as follows. A circle **31** sandwiched between adjacent protrusions **20** and is circumscribed with the base of the protrusion **20** is referred to as the first circle. A circle **32** that is circumscribed with the periphery of the bases of at least three protrusions **20**, and preferably has the largest diameter in the region between the protrusions **20** is referred to as the second circle. Diameter of the second circle **32** is larger than that of the first circle **31**. A circle **33** sandwiched between adjacent protrusions **20** and is circumscribed with the peripheries of the top faces of the protrusions **20** is referred to as the third circle. The protrusions **20** are preferably arranged so that diameter of the third circle **33** becomes larger than that of the second circle **32**.

[0058] In the example shown in **FIG. 19A**, for example, circles of which diameters are the shortest line segments that connect the bases of two protrusions **20** are referred to as the first circle **31**, and the shortest line segments that connect the bases of two top faces are referred to as the third circle **33**. In a region surrounded by three protrusions **20**, a circle that is circumscribed with the periphery of the bases of the three protrusions **20**, and has the largest diameter in the region between the protrusions is taken as the second circle **32**. Diameters of the first circle R_1, the second circle R_2 and the third circle R_3 satisfy the relation $R_3>R_2>R_1$. Crystal quality will be better when this relation is satisfied.

[0059] **FIG. 19B** shows semiconductor crystal grown to a height halfway up the protrusion **20** on a substrate **10** of **FIG. 19A**. Semiconductor crystal **42** grown from the region between the protrusions **20** and semiconductor crystal **41** grown from the top face **20***t* of the protrusion are shown. As can be seen from **FIG. 19B**, since the protrusions are disposed at a distance from each other, the islands of crystal **41** on the top faces of the protrusion grows in the direction of thickness and in the lateral direction as well so as to approach each other. Therefore, the islands of semiconductor crystal **41** growing from the top faces of the protrusions eventually join with each other as the growth proceeds, as indicated by growth prediction circles of dashed lines in **FIG. 19D**. On the other hand, the semiconductor crystal **42** growing from the region between the protrusions **20** grows in the direction of thickness. If the islands of semiconductor crystal **41** growing from the top faces of the protrusions join with each other before thickness of the semiconductor crystal **42** reaches the height of the protrusion, voids are generated. Therefore, occurrence of voids can be suppressed by increasing the distance between protrusions **20**. However, in order to ensure the effect of the substrate with recess/protrusion to extract light, it is preferable to dispose the protrusions **20** as dense as possible. Therefore, it is advantageous to prevent voids and other crystalline defects from occurring while increasing the density of the protrusions.

[0060] According to the present invention, the protrusions having inclined side faces are provided. Thus surface area of the semiconductor crystal **42** growing from the region between the protrusions increases as thickness thereof increases. Also, the area surrounded by the top faces of the protrusions increases. The two conditions described above (high density of protrusions and large distance between protrusions) can be satisfied at the same time. Particularly as shown in **FIGS. 17A and 17B**, when the side face of the protrusion is formed to protrude toward the outside, the semiconductor crystal **41** grown from the top face of the protrusion and the semiconductor crystal **42** grown from the region between the protrusions grow favorably, and it is made possible to prevent the occurrence of abnormal growth and voids. **FIGS. 17A and 17B** are schematic sectional views showing the semiconductor crystal grown halfway up the protrusion **20** on the substrate, showing a part of the cross section of **FIG. 19B**.

[0061] In **FIG. 19B through 19D**, the crystal **41** grown on the top face **20***t* of the protrusion is indicated with hexagon, in order to illustrate the typical form of nitride semiconductor. The present invention can be applied to a case where the crystal grows in other form. In particular, the present invention can be preferably applied to a system where the crystal grows relatively isotropically.

[0062] **FIG. 19C** shows a case where the protrusions are disposed in an arrangement different from that of **FIG. 19A**.

FIG. 19C shows the semiconductor crystal that has been grown halfway up the protrusion **20**, similarly to **FIG. 19B**. In the example shown in **FIG. 19B**, axes **51** and **52** that connect the centers of adjacent protrusions **20** intersect with each other at about 60°, while the protrusions are located at substantially equal spacing on vertices of equilateral triangles. Arrangement of the protrusions in **FIG. 19B** is a periodically repeated pattern of parallelogram (dashed line **53** in the drawing) as a unit in the directions of the axes **51**, **52**. In **FIG. 19C**, axes **51** and **52** that connect the centers of adjacent protrusions **20** intersect with each other perpendicularly, while the protrusions are located at substantially equal spacing on vertices of squares. Arrangement of the protrusions in **FIG. 19C** is a periodically repeated pattern of square (dashed line **53** in the drawing) as a unit in the directions of the axes **51**, **52**.

[**0063**] In **FIG. 19C**, when circles of which diameters are the shortest line segments that connect the bases and top faces of two protrusions **20** are taken as the first circle **31** and the third circle **33**, respectively, the first circle **31** and the third circle **33** are concentric with the center located at the middle point of the line segment that connects the centers of the two protrusions. The circle (the second circle **32**) that has the largest diameter in the region between the protrusions is a circle that is circumscribed with the periphery of the bases of four protrusions. In **FIG. 19C**, too, diameters R_1, R_2 and R_3 of the first circle, the second circle and the third circle, respectively, satisfy the relation $R_3>R_2>R_1$.

[**0064**] In **FIG. 19C**, with a circle that is circumscribed with the periphery of the bases of the three protrusions taken as the second circle **32**, the protrusions may also be arranged so as to satisfy the relation $R_3>R_2>R_1$. This improves a quality of crystal growth.

[**0065**] The embodiments shown in **FIG. 19B**(A) and **FIG. 19C** have common features as follows. First, consider perpendicular bisector of the line segment that connects the centers of the two protrusions **20** that are circumscribed with the second circle **32** having the largest diameter. Then the centers of the first, second and third circles lie on the perpendicular bisector. Second, the second circle **32** intersects with the third circle **33** that is interposed by the protrusions **20** that are circumscribed with the second circle **32**. An arrangement having these two features are preferable because it cause favorable changes in the area and in shape of the crystal **42** growing from the region between the protrusions in the course of growth, thus enabling it to obtain light emitting element having excellent crystallinity.

[**0066**] **FIG. 19D** shows an example where the protrusions **20** having triangular shape in plan view are arranged. In **FIG. 19D**, axes **51** and **52** of the periodical structure of protrusions intersect with each other at about 120°. Unit of the periodical structure is a rhombic cell indicated by dashed line **43**. The sides that constitute the protrusion **20** are parallel to the sides that constitute the adjacent protrusions **20**, with narrow paths formed between adjacent sides. There are the first circle **31** and the third circle **33** on the path. Circumscribed with six protrusions is the second circle **32**. In contrast to the arrangements shown in **FIG. 19B** and **FIG. 19C**, the second circle **32** and the third circle **33** are spaced from each other. The first through third circles in overlapping relationship are selected as follows. First, of the plurality of protrusions that are circumscribed with the second circle, two adjacent ones are selected and the first circle and the third circle interposed by the two protrusions are considered. For the first circle **31** and the third circle **33**, those which are located furthest from the adjacent second circle **32** (in **FIG. 19D**, the second circles **32** located at both ends of the side of the triangle) are taken. In **FIG. 19D**, for example, the first circle **31** and the third circle **33** having centers located on the line segment that connects the middle points of the sides of the protrusion. The same overlapping configuration applies also to the cases of **FIG. 19A** and **FIG. 19C**.

[**0067**] In **FIG. 19D**, diameters R_1, R_2 and R_3 of the first, second and third circles satisfy the relation $R_2=R_3$ and $R_2>R_1$. As shown in **FIG. 19D**, in case the first and third circles are included in the narrow path and the second circle and the third circle do not overlap each other, the islands of semiconductor crystal **41** growing from the top faces of the protrusions may join with each other before the semiconductor crystal **42** growing from the region between the protrusions reaches the top face of the protrusion. If this happens, voids likely to occur in the region **44** enclosed by dashed line in **FIG. 19D**. Even if diameter of the second circle **32** is increased for the purpose of preventing the occurrence of voids, growth in the second circle **32** becomes faster than growth in the first circle **31**, and this difference in the growth rate within the plane may increase the chance of voids to occur, contrary to the intention. This is because, in case the second circle **32** and the third circle **33** do not overlap each other, growth of crystal in around the center of narrow path (around the center of the first circle **31**, region indicated by dashed line **44**) tends to lag behind the crystal growth in the second circle **32**. As a result, the region enclosed by dashed line **44** in **FIG. 19D** can be blocked not only at the top by crystal **41** that has grown from the top face of the protrusion, but also on the side by the crystal grown from the region of the second circle **32**. This may results in the occurrence of voids.

[**0068**] Crystallinity of the semiconductor that grows on the substrate having recess and/or protrusion depends also on the arrangement of the protrusions (or recesses) on the substrate surface. It is preferable to set the plan-view configuration and arrangement of the protrusions so that narrow path is not formed between the protrusions as shown in **FIG. 19A, 19C**. By disposing the protrusions in such an arrangement as diameters of the first, second and third circles satisfy the relationship described above, and preferably the second circle and the third circle overlap each other, it is made possible to further improve the crystallinity of the semiconductor and obtain further better semiconductor element.

[**0069**] While the description in this specification is focused on the case of forming the protrusions on the substrate, the description is applicable to the case of forming recesses on the substrate as well. Those skilled in the art should be able to interpret the description in order to understand the variation.

BRIEF DESCRIPTION OF THE DRAWINGS

[**0070**] **FIG. 1** is a cross sectional view showing an embodiment of a semiconductor device according to the present invention.

[**0071**] **FIGS. 2A through 2E** are diagrams showing a process of manufacturing the semiconductor device shown in **FIG. 1**.

[0072] **FIGS. 3A through 3D** are diagrams schematically showing the propagation of light according to the present invention in comparison to the prior art.

[0073] **FIG. 4A** is a perspective view showing an example of pattern of protrusions in an embodiment of the present invention, and **FIGS. 4B and 4C** are perspective views showing examples of pattern of protrusions in case the side face of protrusion consists of a single sloped surface of the same angle of inclination.

[0074] **FIG. 5A** is a sectional view showing an example of pattern of protrusions in an embodiment of the present invention, and **FIG. 5B** is a sectional view showing an example of pattern in case the side face of protrusion consists of a single sloped surface of the same angle of inclination.

[0075] **FIG. 6** is a cross sectional view showing a semiconductor device according to an embodiment of the present invention.

[0076] **FIGS. 7A through 7H** are perspective views showing other examples of pattern of recess or protrusion.

[0077] **FIGS. 8A through 8D** are diagrams showing variations of the configuration of p-side ohmic electrode.

[0078] **FIGS. 9A through 9C** are diagrams showing other variations of the configuration of p-side ohmic electrode.

[0079] **FIGS. 10A and 10B** are diagrams showing further variations of the configuration of p-side ohmic electrode.

[0080] **FIGS. 11A and 11B** are schematic diagrams explanatory of the direction of arranging the recess or protrusion that are formed in hexagonal shape on a substrate.

[0081] **FIG. 12** is an SEM photograph of a protrusion according to an embodiment of the present invention.

[0082] **FIG. 13** is an SEM photograph of a protrusion according to another embodiment of the present invention.

[0083] **FIG. 14** is an SEM photograph of a protrusion.

[0084] **FIG. 15** is a schematic sectional view showing cross section of protrusion in an embodiment of the present invention.

[0085] **FIGS. 16A and 16B** are perspective views showing the protrusion in an embodiment of the present invention.

[0086] **FIGS. 17A and 17B** are schematic sectional views showing the protrusion formed on the substrate in an embodiment of the present invention, and semiconductor grown thereon.

[0087] **FIGS. 18A through 18F** are schematic sectional views showing manufacturing process for the substrate according to an embodiment of the present invention.

[0088] **FIGS. 19A through 19D** are schematic top views showing the pattern of protrusions formed on the substrate top surface according to an embodiment of the present invention.

[0089] **FIG. 20** is a graph showing electrostatic destruction characteristic according to an embodiment of the present invention.

[0090] **FIG. 21** is a graph showing luminance of light emitting device according to an embodiment of the present invention.

[0091] **FIGS. 22A through 22C** are a top view showing the structure of light emitting device according to an embodiment of the present invention **(FIG. 22A)**, a sectional view showing the layer structure thereof **(FIG. 22B)** and a circuit diagram of the layer structure thereof **(FIG. 22C)**.

[0092] **FIG. 23** is a schematic diagram showing the light emitting device according to an embodiment of the present invention.

[0093] **FIG. 24** is a schematic sectional view showing the light emitting device according to an embodiment of the present invention.

[0094] **FIGS. 25A and 25B** are a top view showing the light emitting device according to an embodiment of the present invention **(FIG. 25A)** and a partially sectional schematically view showing the structure thereof along line A-A **(FIG. 25B)**.

[0095] As described above, according to the present invention, undesirable light propagation in the light emitting device can be suppressed by forming recesses and/or protrusions in the substrate surface, which results in an improved light extracting efficiency. Also, occurrence of pits or voids due to the recesses and/or protrusions can be suppressed. Therefore, a high-performance semiconductor device can be provided.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0096] Now the present invention will be described in detail with reference to the accompanying drawings. **FIG. 1** shows a preferred embodiment of the semiconductor device according to the present invention, wherein an n-type semiconductor layer **11**, an active layer **12** and a p-type semiconductor layer **13** are formed successively on a substrate **10**. The substrate **10** has protrusions **20** formed in a repetitive pattern in the surface thereof.

[0097] Height of the protrusion **20** (depth of recess if the space between two protrusions is regarded as recess) is preferably in a range from 0.1 μm to 2 μm inclusive. Length "a" of one side of the protrusion **20** if it is a polygon, or diameter of the protrusion if it is circle is preferably in a range from 1 μm to 10 μm inclusive. Distance between adjacent protrusions **20** is preferably in a range from 1 μm to 10 μm inclusive.

[0098] The process of manufacturing the semiconductor shown in **FIG. 1** will now be described with reference to **FIGS. 2A through 2E**. First, as shown in **FIG. 2A**, a protective film **25** is formed as an etching mask on the substrate **10**. The substrate **10** may be made of sapphire, Si, SiC or the like.

[0099] Then as shown in **FIG. 2B**, the protective film **25** is formed into a pattern. The pattern of the protective film **25** in plan view may be, for example, as shown in **FIGS. 7A through 7H** (hatching in **FIGS. 7A through 7H** indicates the region where the protective film is formed). **FIGS. 7A through 7D** show examples of the protective film when protrusions are formed on the substrate. When recesses are formed on the substrate, the protective film may be formed

in the patterns shown in **FIGS. 7E through 7H**. When the recesses or the protrusions are formed in circular or polygonal shape, it is preferable to arrange them in a hexagonal pattern in order to reduce pits. In the example shown in **FIG. 2B**, the protective film is formed in a circular pattern as shown in **FIG. 7A**.

[**0100**] Then as shown in **FIG. 2C**, surface of the substrate **10** exposed through the protective film **25** is etched. At this time, the protective film **25** is also etched to some extent. Either dry etching or wet etching may be employed in this etching process. Among these, dry etching is preferable. Specifically, gas phase etching, plasma etching, reactive plasma etching (such as RIE, magnetron RIE), ECR plasma etching, sputter etching, ion beam etching and photo-etching. Reactive ion etching (RIE), above all, is preferably used. For the etching gas, Cl_2 compound or F compound such as Cl_2, $SiCl_4$, BCl_3, HBr, SF_6, CHF_3, C_4F_8 or CF_4 can be used. An inert gas such as Ar may also be used. In the first and second steps of etching, a gas having high selective etching capability for the substrate and the mask is preferably used, such as a mixture gas of $SiCl_4$ and Cl_2, in the case of sapphire substrate and mask made of SiO_2. In the third step, a gas having selectivity different from that of the second step, preferably a gas having lower selectivity is used, such as CF_4, CHF_3 or Ar can be used. After etching the exposed surface of the substrate, the protective film is removed and the substrate is etched further. This results in the formation of the protrusions **20** having two sloped surfaces in the surface of the substrate **10**. Instead of this method, the protrusions **20** having two sloped surfaces may also be formed by continuing the etching still after the protective film has been completely removed in the process shown in **FIG. 2C**. The protrusions **20** having two sloped surfaces may also be formed by changing the etching rate or apparatus amid the course. Recesses having two sloped surfaces may be formed by changing the etching rate or other method. For example, after etching the substrate to some extent, etching may be continued with a slower etching rate, so as to form recesses having two sloped surfaces.

[**0101**] Then as shown in **FIG. 2E**, the n-type semiconductor layer **11**, the active layer **12** and the p-type semiconductor layer **13** are formed successively one on another in this order on the substrate **10** whereon the protrusions **20** are formed in an ordered pattern.

[**0102**] Growth of a semiconductor, including GaN semiconductor, on a substrate is significantly affected by the surface condition of the substrate. In case the side face (sloped surface) of the protrusion is formed in one step as shown in **FIG. 5B**, significant notches are formed on the side face of the protrusion along the slope as shown in the SEM photograph of **FIG. 14**. This situation is schematically shown in **FIG. 4B** and **FIG. 4C**. Presence of the notches increases the possibility of voids to be generated when growing the semiconductor. This is because not only the surface roughness of the side face is different between adjacent protrusions **20**, but also there is significant difference in the surface roughness within a single protrusion. In consequence, semiconductor grows at different rates near the side face of the protrusion, fast at one point and slowly at another, so that the semiconductor grown at the fast growing point spreads over the slow growing point. As a result, voids can easily develop in the semiconductor.

[**0103**] In this embodiment, in contrast, the side face (sloped surface) of the protrusion is formed in two steps as shown in **FIG. 5A**. Therefore, while the first sloped surface near the substrate includes some notches, the second sloped surface located above is almost free from notches, as shown in **FIG. 12**. This situation is schematically shown in **FIG. 4A**, which is a perspective view showing the protrusion **20** schematically. The first sloped surface **22** and the second sloped surface **23** are formed in this order from the bottom of the substrate. Although the first sloped surface **22** includes some notches **24**, the second sloped surface **23** is almost free from notches. Thus in this embodiment, generation of voids is suppressed by the second sloped surface **23** that is free from notches.

[**0104**] Then the device forming process is carried out with electrode formed, so as to finish the LED chip. Holes and electrons are injected from the n-type semiconductor layer **11** and the p-type semiconductor layer **13** into the active layer **12**, where both charges recombine thereby to emit light. The light is extracted through the sapphire substrate **10** or the electrode formed on the p-type semiconductor layer **13**.

[**0105**] In the case of a semiconductor light emitting device of the prior art having flat substrate, as shown in **FIG. 3A**, light that is generated in the active layer **12** and is incident on the interface between the p-type semiconductor layer **13** and the electrode or on the interface between the n-type semiconductor layer **11** and the substrate **10** with an angle of incidence equal to or larger than the critical angle is captured within the waveguide so as to propagate laterally.

[**0106**] In case the protrusions **20** are formed on the surface of the substrate **10** as shown in **FIG. 3B** or **FIG. 3C**, light that is incident on the interface between the p-type semiconductor layer **13** and the electrode or on the interface between the n-type semiconductor layer **11** and the substrate **10** with an angle of incidence equal to or larger than the critical angle is scattered or diffracted. Most of the scattered or diffracted light is incident on the interface between the p-type semiconductor layer **13** and the electrode or on the interface between the n-type semiconductor layer **11** and the substrate **10** with an angle of incidence smaller than the critical angle, and can be extracted to the outside. In case the side face of the protrusion **20** is formed from a sloped surface with a single angle of inclination as shown in **FIG. 3B** or **FIG. 3C**, however, voids are likely to be generated in the semiconductor layer **11**. When voids are generated in the semiconductor layer, crystallinity of the semiconductor becomes lower and the quantum efficiency decreases. In this embodiment, for this reason, side face of the protrusion is formed from two sloped surfaces of different angles of inclination so as to suppress the generation of voids, as shown in **FIG. 3D**. This constitution makes it possible to efficiently extract light that has been generated in the active layer and improve the crystallinity of the semiconductor, thereby providing a semiconductor device of higher output power.

[**0107**] In case the contact electrode provided on the p-type semiconductor layer **13** is a transparent electrode, the device is mounted face up but, in the case of reflecting electrode, the device is mounted face down. The present invention is effective in either mode of mounting. Even in the case of reflective electrode, the device can be mounted face up when

the electrode has opening or notch. In this case, too, the present invention achieves conspicuous effect.

[0108] The embodiment described above is an example where the protrusion **20** has a circular shape in plan view, although the protrusion **20** may also be formed in a polygonal shape. In case the substrate **10** is made of sapphire and the semiconductor **11** is made of GaN, in particular, the GaN grows with an offset angle of 30 degrees from the lattice of the sapphire substrate. Therefore, it is preferable to form the protrusion **20** on the sapphire substrate **10** in such a shape as follows. Shape of the protrusion **20** in plan view is formed in a polygon that has sides substantially parallel to A planes (11-20), (1-210) and (−2110) of GaN and vertices in stable growth planes (1-100), (01-10) and (−1010) of GaN. This polygon does not have any side that is parallel to the stable growth planes (1-100), (01-10) and (−1010) of GaN, namely M-plane. By forming the protrusion **20** in such a shape, it is made possible to grow a flat GaN layer with high crystallinity.

[0109] Specifically, in case the protrusion **20** has a shape of equilateral triangle in plan view, it is preferable to form the equilateral triangle from sides that cross (are not parallel to) M-plane which is the stable growth plane of GaN, when viewed from above. It is more preferable to form the equilateral triangle from sides that are perpendicular to straight lines connecting the center and vertices of an equilateral hexagon that is defined by planes parallel to A-axis (more specifically, by intersection lines between the planes and the substrate surface) of the nitride semiconductor as its sides, in other words, a equilateral hexagon that is defined by A-axis of the nitride semiconductor as its sides. By forming the protrusion **20** in such a shape, it is made possible to grow a flat GaN layer that fills the surrounding of the protrusion **20** with high crystallinity.

[0110] This is supposedly because the growing rate of GaN becomes higher in a portion where GaN grown from the top face of the protrusion **20** and GaN grown on the flat surface where the protrusion **20** is not grown join. While GaN is grown from the top face of the protrusion **20** in hexagonal crystal structure consisting of sides that are parallel to A-axis, growing rate of GaN is higher near the side face of the protrusion **20** where GaN grown from the top face of the protrusion **20** and GaN grown on the flat surface join each other. As a result, growth of GaN near the side face of the protrusion **20** catches up the growth in other regions so that flat GaN layer is obtained.

[0111] The protrusion **20** may also be formed in an equilateral hexagonal shape. In this case, if the orientation flat "a" of the sapphire substrate **10** having principal plane in C-face lies in A face, for example, the equilateral hexagonal shape may be arranged in direction shown in either **FIG. 11A** or **FIG. 11B**. In case GaN is grown on C plane of the sapphire substrate as described previously, A plane of the sapphire substrate and M-plane of GaN become parallel to each other. Therefore, it is preferable to arrange the recess or protrusion of equilateral hexagon as shown in **FIG. 11A**, in which case the sides that constitute the equilateral hexagon cross at right angles to one of the M-planes that are stable growth plane of GaN, when viewed from above the substrate. In other words, this means that the equilateral hexagon is formed from sides that are perpendicular to the straight lines that connect the center and vertices of an equilateral hexagon that is defined by M-planes of GaN as its sides, when viewed from above the substrate.

[0112] The above embodiments of the present invention will now be described in more detail below.

Embodiment 1

[0113] In the first embodiment of the present invention, the side face of the protrusion consists of at least two sloped surfaces (first sloped surface **22**, second sloped surface **23**) as shown in **FIG. 4A** and **FIG. 5A**. The inclination angle θ_2 on the top face side of the protrusion is smaller than the inclination angle θ_1 on the bottom side. The inclination angle θ is the angle between the side face and the bottom of the protrusion. In case recesses are formed in the substrate, inner wall of the recess is also formed so that the inclination angle θ_2 of the upper inner wall is larger than the inclination angle θ_1 of the lower inner wall. The inclination angle θ_1 of the inner wall is the complementary angle of the angle ϕ_i between the inner wall and the bottom surface of the recess.

$$\theta_i=180^\circ-\phi_i(i=1, 2)$$

[0114] When the inclination angle θ_3 is defined as the angle between the top face and the side face of the protrusion, in case the top face is substantially parallel to the substrate surface, the angle ϕ_2 between the upper inner wall and the bottom surface of the recess is nearly equal to the inclination angle θ_3 of the protrusion. Preferably, the first sloped surface **22** and the second sloped surface **23** are located at the top and bottom of the protrusion and/or the recess, respectively. This makes manufacturing easier, causes the semiconductor layer to grow favorably to near the protrusion and enables it to suppress the occurrence of pit and voids.

Embodiment 2

[0115] In the second embodiment of the invention, side face of the protrusion is formed in a curved surface. In case entire side face of the protrusion is formed in a single curved surface, radius of curvature may be made larger on the top face side and smaller on the bottom side. Alternatively, such a configuration may also be employed as the bottom side is flat, i.e., upper side of the side face is curved and the lower side is flat. Moreover, a plurality of curved portions and a plurality of flat portions may be formed on the side face of the protrusion. For example, in the structure of the first embodiment where the first and second sloped surfaces are formed, the second sloped surface may be formed in a curved surface with the first sloped surface consisting of substantially flat surface. Condition of the side face may be selected as required in accordance to the substrate material, etching condition, material of the semiconductor layer and other factors.

[0116] It is preferable to form the entire side face in a curved surface and make the inclination angle θ_2 on the top face side of the protrusion smaller than the inclination angle θ_1 on the bottom side, as shown in **FIG. 15**. This configuration makes the changes in the shape and surface area of the semiconductor layer growing on the substrate smoother. That is, better crystal can be grown while suppressing the occurrence of abnormal crystal growth. The inclination angle θ_m can be decreased when the side face is formed in a single curved surface rather than having a partially curved portion or a plurality of curved surfaces. If the inclination

angle θ_m can be decreased, ratio of the area of the side face to the area of the substrate surface can be increased so as to achieve higher efficiency of extracting light.

Embodiment 3 (Structure of Light Emitting Device)

[0117] Constitution of the semiconductor light emitting device according to the present invention will be described in detail. There are no specific requirements for the size and thickness of the substrate **10** which may be of any constitution as long as it allows epitaxial growth of semiconductor thereon. The substrate used to grow the nitride semiconductor thereon may be made of an insulating material such as sapphire or spinel ($MgAl_2O_4$) having principal plane in C plane, R plane or A plane, or an oxide such as lithium niobate or neodymium gallate that forms lattice junction with silicon carbide (6H, 4H, 3C), silicon, ZnS, ZnO, Si, GaAs, diamond, or oxide substrates such as lithium niobate or neodymium gallate which can provide a good lattice match with nitride semiconductor. A substrate made of nitride semiconductor such as GaN or AlN may also be used provided that it is thick enough to form devices thereon (over several tens of micrometers). A substrate made of different material may be cut with offset angle. If C plane of sapphire is used, offset angle is preferably in a range from 0.01° to 3.0°, and more preferably from 0.05° to 0.5°.

[0118] The semiconductor light emitting device according to the present invention may have such a structure as electrodes of different types of electrical conductivity are provided on the same side of the substrate as shown in **FIG. 6**, **FIG. 25A** and **FIG. 25B**. An electrically conductive substrate may also be used with electrodes for first conductivity type layer and second conductivity type layer provided on opposite sides of the substrate, respectively.

[0119] In case nitride semiconductor is used as the semiconductor, it is preferable to use nitride semiconductor having composition represented by general formula $In_xAl_yGa_{1-x-y}N$ ($0 \leqq x$, $0 \leqq y$, $x+y \leqq 1$). B, P or As may be included in the nitride semiconductor as mixed crystal. The n-type nitride semiconductor **11** and the p-type nitride semiconductor **13** may be formed in either single layer or multi-layer structure. The nitride semiconductor is doped with n-type impurity or p-type impurity. As the n-type impurity, group IV elements or group VI element such as Si, Ge, Sn, S, O, Ti, Zr may be used and preferably Si, Ge or Sn are used and more preferably Si is used. While there is no restriction on the p-type impurity, Be, Zn, Mn, Cr, Mg or Ca may be used and Mg is preferably used. Thus both types of nitride semiconductor can be formed. The active layer **12** is preferably formed in single quantum well (SQW) structure or multiple quantum well (MQW) structure.

[0120] The embodiments shown in **FIG. 6** and **FIG. 25** have such a structure as the light emitting element **101** is formed on the substrate **10**, with electrodes **16**, **14** provided on the layers **11**, **13** of different conductivity types, respectively, of the light emitting element. While the device structure made by stacking the p-type layer **13** and the n-type layer **11** in a particular order is described as an example in this specification, the order of stacking the layer is not restricted to that described in the specification. The light emitting device may have any proper structure as long as it has at least the layer of first conductivity type **11** and the layer of second conductivity type **13**. More preferably, the active layer **12** is provided between the layer of first conductivity type **11** and the layer of second conductivity type **13**. Alternatively, a base layer **11***a* that provides a base for the element structure **101** may be formed between the substrate **10** and the n-type layer **11***b* of the layer of first conductivity type as shown in **FIG. 25B**.

[0121] Now the method of manufacturing the light emitting device shown in **FIG. 6** will be described below.

[0122] It is preferable to form a buffer layer (not shown) before growing the n-type nitride semiconductor **11** on the substrate **10**. The buffer layer is preferably made of a nitride semiconductor represented by general formula $Al_aGa_{1-a}N$ ($0 \leqq a < 0.8$), more preferably a nitride semiconductor represented by general formula $Al_aGa_{1-a}N$ ($0 \leqq a \leqq 0.5$). Thickness of the buffer layer is preferably in a range from 0.002 to 0.5 μm, more preferably from 0.005 to 0.2 μm, and most preferably 0.01 to 0.02 μm. Semiconductor layers of better crystallinity can be formed on the substrate by making the thickness of the buffer layer smaller than the height of the protrusion (or depth of the recess) of the substrate. For example, the semiconductor layer of satisfactory crystal structure can be made with less voids, pits and dislocations. The buffer layer is grown at a temperature preferably in a range from 200 to 900° C., and more preferably from 400 to 800° C. This makes it possible to reduce dislocations and pits generated on the nitride semiconductor. An $Al_xGa_{1-x}N$ ($0 \leqq x \leqq 1$) layer may also be formed by ELO (epitaxial lateral overgrowth) method on the substrate made of different material. The ELO (epitaxial lateral overgrowth) method is a process of growing nitride semiconductor in lateral direction so as to bend and converge threading dislocation and decrease dislocations. The buffer layer may be formed in multiple layer structure, such that includes a low-temperature growth layer and a high-temperature growth layer. The high-temperature growth layer may be a GaN layer grown without doping or one that is doped with an n-type impurity. Thickness of the high-temperature growth layer is preferably 1 μm or larger, and more preferably 3 μm or larger. The high-temperature growth layer is grown at a temperature preferably in a range from 900 to 1100° C., and more preferably at 1050° C. or higher.

[0123] Then the n-type semiconductor layer **11** is grown. First, an n-type contact layer is grown. The n-type contact layer has such a composition that has band gap energy larger than that of the active layer, preferably $Al_jGa_{1-j}N$ ($0<j<0.3$). While there is no limitation to the thickness of the n-type contact layer, it is preferably 1 μm or larger, and more preferably 3 μm or larger. Then an n-type cladding layer is grown. The n-type cladding layer includes Al. While there is no limitation to the concentration of the n-type impurity, it is preferably in a range from 1×10^{17} to $1\times10^{20}/cm^3$, more preferably from 1×10^{18} to $1\times10^{19}/cm^3$. The n-type impurity may also be included with graded concentration. When the Al content is graded, the cladding layer can also perform a better function of carrier confinement.

[0124] The active layer **12** used in the present invention is preferably formed in such a quantum well structure that consists of at least a well layer having composition of $Al_aIn_bGa_{1-a-b}N$ ($0 \leqq a \leqq 1$, $0 \leqq b \leqq 1$, $a+b \leqq 1$) and a barrier layer having composition of $Al_cIn_dGa_{1-c-d}N$ ($0 \leqq c \leqq 1$, $0 \leqq d \leqq 1$, $c+d \leqq 1$). Output power of the light emitting device can be made higher by forming the active layer from nitride

semiconductor without doping or while doping with an n-type impurity. It is more preferable the well layer is grown without doping and the barrier layer is grown while doping with an n-type impurity in order to increase the output power and light emission efficiency of the light emitting device. When Al is included in the well layer of the light emitting device, it is made possible to emit light in a wavelength region where it is difficult to emit light with the conventional well layer made of InGaN, namely wavelengths near 365 nm, that corresponds to the band gap energy of GaN, and shorter.

[0125] Thickness of the well layer is preferably in a range from 1 nm to 30 nm inclusive, more preferably from 2 nm to 20 nm inclusive and most preferably from 3.5 nm to 20 nm inclusive. When smaller than 1 nm in thickness, the layer cannot satisfactorily function as the well layer. When the thickness is 2 nm or more, relatively homogeneous layer can be obtained without fluctuation in thickness. When the thickness is 3.5 nm or more, output power can be increased further. This is because a thicker well layer allows for injection of more carriers so as to emit light with high efficiency and high internal quantum efficiency through recombination of carriers as in an LD driven with a high current, and this effect is remarkable particularly in a multiple quantum well structure. In the case of single quantum well structure, the effect of increasing the output power similarly to the above can be achieved by setting the thickness to 5 nm or more. When the well layer is thicker than 30 nm, on the other hand, crystallinity of quaternary mixed crystal of InAlGaN becomes lower, resulting in lower performance of the device. By setting the thickness of the well layer to 20 nm or less, it is made possible to grow the crystal while suppressing the occurrence of crystal defects. While there is no limitation to the number of well layers, it is preferable to provide four or more well layers which enables it to set the thickness of the well layer to 10 nm or less and decrease the thickness of the active layer. This is because the thicker the layers that constitute the active layer, the thicker the active layer and higher the value of Vf becomes. In the case of multiple quantum well structure, it is preferable that at least one of the plurality of well layers is not thicker than 10 nm, and it is more preferable that all well layers are not thicker than 10 nm.

[0126] The barrier layer, similarly to the well layer, is preferably doped with an n-type impurity or undoped. In case the barrier layer is doped with an n-type impurity, concentration of the n-type impurity is preferably 5×10^{16}/cm^3 or higher. In the case of LED, the concentration is preferably in a range from 5×10^{16} to 2×10^{18}/cm^3. In the case of high output LED or LD, the impurity concentration is preferably in a range from 5×10^{17} to 1×10^{20}/cm^3, and more preferably in a range from 1×10^{18} to 5×10^{19}/cm^3. In this case, it is preferable that the well layer either does not substantially include n-type impurity or is undoped. When the barrier layer is doped with an n-type impurity, either all barrier layers in the active layer may be doped, or some of the barrier layers may be doped while leaving the others undoped. In case only some of the barrier layers are doped with n-type impurity, it is preferable to dope the barrier layers that are located on the n-type layer side in the active layer. When the nth barrier layer Bn (n is a positive integer) from the n-type layer side is doped, for example, preferably the first through nth barrier layers are all doped with impurity, such a light emitting device can be made as electrons are efficiently injected into the active layer so as to achieve high efficiency of light emission and high internal quantum efficiency. With regard to the well layer, too, an effect similar to that of the barrier layer can be achieved by doping the mth well layer Wm (m is a positive integer) from the n-type layer side. Similar effect can also be achieved by doping both the barrier layer and the well layer.

[0127] Then a plurality of layers as described below are formed as the p-type nitride semiconductor layer **13** on the active layer **12**. As for the p-type cladding layer, while there are no limitations to the composition as long as it has band gap energy larger than that of the active layer so as to be capable of confining the carrier within the active layer, the composition is preferably $Al_kGa_{1-k}N$ ($0\leqq k<1$), and more preferably $Al_kGa_{1-k}N$ ($0<k<0.4$). While there is no limitation to the thickness of the p-type cladding layer, it is preferably in a range from 0.01 to 0.3 μm, and more preferably from 0.04 to 0.2 μm. Concentration of the p-type impurity is preferably in a range from 1×10^{18} to $1\times10^{21/cm3}$, more preferably from 1×10^{19} to 5×10^{20}/cm^3. The p-type impurity in the range described above enables it to decrease the bulk resistivity without deteriorating the crystallinity. The p-type cladding layer may be formed either in single layer structure or multiple layer structure (super lattice structure). In the case of multiple layer structure, it may comprises a layer represented by $Al_kGa_{1-k}N$ described above and other nitride semiconductor layers having a band gap energy smaller than that of the former. The layer of smaller band gap energy have a composition represented by $In_lGa_{1-l}N$ ($0\leqq l<1$) or $Al_mGa_{1-m}N$ ($0\leqq m<1$), similarly to the case of the n-type cladding layer. Thickness of each layer constituting the multiple layer structure in the case of super lattice structure is preferably 100 Å or less, more preferably 70 Å or less and most preferably in a range from 10 to 40 Å. In case the p-type cladding layer is formed in multiple layer structure consisting of layers having larger band gap energy and layers having smaller band gap energy, the p-type impurity may be added to at least either the layers having larger band gap energy or the layers having smaller band gap energy. When both the layers having larger band gap energy and the layers having smaller band gap energy are doped, the doses may be the same or different.

[0128] Then a p-type contact layer is formed on the p-type cladding layer. The p-type contact layer is preferably formed in composition of $Al_fGa_{1-f}N$ ($0\leqq f<1$), and more preferably $Al_fGa_{1-f}N$ ($0\leqq f<0.3$) which enables it to achieve good ohmic contact with the p electrode **14** that is an ohmic electrode. Concentration of the p-type impurity is preferably 1×10^{17}/cm^3 or higher. It is preferable that the p-type contact layer has such a graded composition as the p-type impurity concentration is higher and mix proportion of Al is lower on the electrically conductive substrate side. In this case, the composition may be graded either continuously or stepwise. For example, the p-type contact layer may be constituted from a first p-type contact layer that makes contact with the ohmic electrode and has high p-type impurity concentration and low Al content, and a second p-type contact layer that has low p-type impurity concentration and high Al content. The first p-type contact layer enables it to achieve good ohmic contact and the second p-type contact layer suppresses self-absorption of the emitted light.

[0129] After forming the nitride semiconductor layers on the substrate **10** in the process described above, the wafer is

taken out of a reaction apparatus and is subjected to heat treatment at 400° C. or higher in an atmosphere that includes oxygen and/or nitrogen. This process removes hydrogen that is bonded in the p-type layer, so as to form the p-type nitride semiconductor layers that show p-type conductivity.

[0130] Then the p-type electrode **14** that achieves ohmic contact is formed on the surface of the p-type contact layer. The p-type electrode may be formed by CVD process, sputtering, vapor deposition or the like. The p-type electrode is preferably formed from the material described previously. Sheet resistance can be decreased by forming in multiple layer structure of two or more layers with the total thickness of 50000 Å or less, compared with a singular layer structure having a uniform thickness.

[0131] The p-type electrode may be formed in various shapes such as rectangular, stripes, square or lattice in plan view. For example, the p-type electrode **14** may be formed over the entire surface of the p-type semiconductor layer, then openings **18** are formed in dots as shown in **FIG. 8A** and **FIG. 8B**. The p-type electrode may also be formed in such shapes as rhombic, parallelogram, mesh, stripes or comb as shown in **FIG. 8C** and **FIG. 8D**. A branching shape such that a single stem branches into a plurality of portions as shown in **FIG. 9A** and **FIG. 10A** may also be employed. Plurality of branch electrodes that are electrically connected may be formed in stripes while the p-type electrode has openings **18** as shown in **FIG. 9C** and **FIG. 10B**. Moreover, circular pattern may be employed. By using such a p-type electrode structure in combination with the substrate having the recess or protrusion formed thereon, the efficiency of extracting light can be further improved.

[0132] In the case of p-type electrode having a plurality of through holes **18** that reach the surface of the p-type semiconductor layer and are surrounded by the electrodes, area S of the portion surrounded by the outermost periphery of the p electrode (total area of the electrode including the openings) and total length L of the circumference of the openings preferably satisfy a relation $L/S \geqq 0.024\ \mu m/\mu m^2$. This enables it to make a semiconductor light emitting device that allows efficient emission of light from the surface of the p-type semiconductor layer and has a low value of Vf.

[0133] The plurality of openings preferably have substantially identical shapes, which makes it easier to form the openings and achieves uniform light emission in the surface. It is also preferable that each of the plurality of openings has substantially the same area, which also contributes to achieving uniform light emission in the surface.

[0134] The p electrode **14** is an ohmic electrode used for supplying current to the device through ohmic contact with the surface of the p-type nitride semiconductor layer **13**. In a nitride semiconductor device, it is a common practice to form a p pad electrode **15** for connection by wire bonding, besides the p electrode **14** for ohmic contact, and connect the p pad electrode **15** and the p electrode **14** that is an ohmic electrode. The p pad electrode **15** may be either provided on the p-side layer **13**, or provided outside of the p-side layer **13** with metal wiring, for example, via an insulating film on the n-type layer **11** whereon the n-type electrode **16** is formed. When the p pad electrode **15** is formed on the p-side layer **13**, the p pad electrode **15** may partially overlap the p electrode **14**, or the p pad electrode **15** may be formed on the p electrode **14**. Since the p pad electrode **15** is provided for the purpose of packaging with wires, it may have any thickness as long as it does not damage the semiconductor device when mounting. In case light is extracted from the side where the p-type electrode **15** is formed, it is necessary to form the p-type electrode **15** as small as possible.

[0135] The p-type electrode **15** is preferably made of a material that bonds well. Specifically, Co, Fe, Rh, Ru, Ti, V, Cr, Zr, Nb, Mo, Hf, Ta, W, Re, Mn, Al, Zn, Pt, Au, Ru, Pd or Rh may be used. Preferably, at least one kind selected from among a group consisting of Ag, Al, Pt, Cu, Ni, Ti, Au and Rh and oxide, nitride and the like thereof are used. More preferably, at least one kind selected from among a group consisting of Ag, Al and Pt is used. The p pad electrode may be made in single layer, alloy or multiple layers.

[0136] The n electrode **16** is formed on the surface of the n-type contact layer. For the n electrode **16**, in addition to the electrode described above, W/Al, Ti/Al, Ti/Al/Ni/Au, W/Al/W/Pt/Au or Al/Pt/Au or the like may be used. Thickness of the n electrode **16** is preferably in a range from 0.1 to 1.5 μm. The n electrode **16** serves as a pad electrode for bonding as well as making ohmic contact. The n electrode **16** may also be formed in two layers of a pad electrode for bonding and an ohmic electrode that makes ohmic contact with the n-side layer **11**, which may be formed at the same time in substantially the same shape. The n electrode for ohmic contact and the n pad electrode may also be formed one on another in different processes in different shapes.

[0137] Forming the electrode on the nitride semiconductor layer and then applying heat treatment makes it possible to accelerate alloy formation, achieve good ohmic contact with the semiconductor layer, and decrease the contact resistance between the semiconductor layer and the electrode. Temperature of heat treatment is preferably in a range from 200 to 1200° C., more preferably in a range from 300 to 900° C. and most preferably in a range from 450 to 650° C. It is preferable that the ambient gas includes oxygen and/or nitrogen. The heat treatment may also be carried out in an ambient gas that includes inert gas such as Ar or in air atmosphere.

[0138] The semiconductor device of the present invention may have a protective film **17** formed from SiO_2, ZrO_2, TiO_2, Al_2O_3, or an oxide that includes at least one element selected from among a group consisting of V, Zr, Nb, Hf, Ta or SiN, BN, SiC, AlN, AlGaN, etc. Continuously on the side face of the device where the nitride semiconductor layers are stacked. The protective film is preferably an insulating film, which enables it to make a semiconductor device of high reliability. When the insulating film is provided on the surface of the p-type layer where the electrode is not formed, it is made possible to effectively suppress the migration of the electrode.

[0139] Then the wafer is divided by scribing or dicing into the chips of nitride semiconductor device whereon the electrodes are formed as shown in **FIG. 6**.

[0140] This embodiment has been described for a case where light is extracted from the surface of the nitride semiconductor layer where the electrode is formed, although light may also be extracted from the substrate side. In this case, the p-side pad electrode **15** is preferably formed in oval shape as shown in **FIG. 9B**. A metallization layer (bump) is formed on the p-side pad electrode **15**, instead of wire, for

the connection with external electrodes or the like, for face down mounting as shown in **FIG. 22B**. The metallization layer may be made of Ag, Au, Sn, In, Bi, Cu, Zn or the like. In the case of face down mounting, the pad electrode is heated and expands in volume which, together with the pressure applied, causes the material that makes the pad electrode likely to flow toward the side face. In the nitride semiconductor light emitting device of this embodiment, however, such trouble can be prevented since the electrode is alloyed as described above. The structure of this embodiment also has high heat dissipating characteristic and improved reliability.

[**0141**] The semiconductor device of the present invention, in the case of gallium nitride-based semiconductor light emitting device (which includes at least gallium and nitrogen), for example, white light can be emitted with high output power by applying a mixture of fluorescent material and a resin to the surface of the light emitting device whereon the electrode has been formed.

[**0142**] The light emitting element **100** of the present invention may have such a structure that is with the electrodes **14** and **16**, one piece each, of the layers **11**, **13** of the first and second conductivity types provided on the same side of the substrate, as shown in **FIG. 8A**, **FIG. 8B**, **FIG. 9A**, **FIG. 9B** and **FIG. 10A**. Alternatively, as shown in **FIG. 9CFIG. 10B**, **FIG. 22A** and **FIG. 25A**, one or both of the electrodes **14**, **16** of the layers **11**, **13** of different conductivity types is formed in plurality in one light emitting device. As explained in **FIG. 25B**, structure of the light emitting element is such that a light emitting portion **151** having the layers **11**, **13** of the first and second conductivity types and preferably the active layer **12** interposed therebetween, a non-light emitting portion **152**, where the layer of first conductivity type is exposed and electrode is provided, are provided in the substrate surface. The electrodes **14**, **16** of the layers **11**, **13** of different conductivity types are provided in plurality, making pairs. The electrode **14** and **16** have extended portions **14***x* and **16***x*, respectively, so that the light emitting portion **151** is interposed by the extended portions **14***x* and **16***x*. The light emitting device can be divided into a functional part **157** which receives electric current and functions as the light emitting element and a non-functional part **158** that is mostly passive such as the portion surrounding the light emitting element. The functional part **157** includes at least one light emitting portion **151** and the non-light emitting portion **152** where electrodes are formed. The non-functional part **158** consists mainly of the non-light emitting portion **152**.

[**0143**] The light emitting device shown in **FIGS. 9C, 10B** and **25**A has a plurality of light emitting portions **151** provided on the substrate, and the light emitting portions **151** are connected to each other, for example, as shown in **FIGS. 25A and 25B**. The electrodes **16** of the layer **11** of the first conductivity type, namely the electrode forming portions **152** are also provided in plurality. The light emitting device **100** shown in **FIG. 22A**, in contrast, has a plurality of light emitting portions **151**, but the light emitting portions **151** are separate from each other. The plurality of electrodes of the electrode forming portion **152** are also provided separately. In this way, plurality of the light emitting portions may be provided while being separated from or connected to each other in the light emitting device **100** (or functional portion **157**).

[**0144**] According to the present invention, as shown in **FIG. 3**, transverse propagation of light in the element **101**, particularly in the layer **11** of the first conductivity type that constitutes the light emitting portion **151** is suppressed by the recess or protrusion **20** formed on the surface of the substrate **10**, thus enabling it to extract light efficiently. Particularly in a region where the layer of the first conductivity type is exposed, since a strong optical waveguide is formed by air (or a protective film), the layer of the first conductivity type and substrate, transverse propagation of light is likely to occur. Even in such a region, transverse propagation of light can be changed into longitudinal direction by providing the recesses or protrusions **20** on the substrate, so as to extract light efficiently in the direction perpendicular to the substrate surface (on the side where the element is formed, or on the opposite side where the substrate is exposed).

[**0145**] A light propagating region exists on the substrate side from the exposed portion **11***s* of the layer of the first conductivity type, also in the non-functional portion **158**. Therefore, light propagation loss can be reduced also in the non-functional portion **158** by providing the recesses or protrusions **20** on the substrate.

[**0146**] In the case of a light emitting device that emits light from the electrode forming surface thereof, an electrode **14** that is permeable to light is provided by means of translucent material or an opening in the light emitting portion **151**. Even in such a case, the electrode **16** and a pad **16***b* of the layer **11** of the first conductivity type, or a pad electrode **15** and a pad **15***b* of the layer of the second conductivity type are not transparent in most cases. When this is the case, light is extracted from a region where the non-transparent electrode is not formed. Therefore, it is particularly preferable that recesses or protrusions are provided on the substrate in the region where the non-transparent electrode is not formed (for example, the region of the non-light emitting portion **152** where the non-transparent electrode is not formed). When light is extracted from the electrode forming surface, while it is important that the electrode **14** formed on the light emitting portion **151** is permeable to light, other electrodes may also be made permeable to light. For example, the electrode **16** of the layer **11** of the first conductivity type and also the pad electrodes may be made permeable to light.

[**0147**] In the light emitting device that has large area and a plurality of light emitting portions as shown in **FIGS. 9C, 10B**, **22**A and **25**A, distribution of light intensity within plane is likely to occur. For example, there occurs difference in light intensity in the light emitting portions **151**, the non-functional portion **152** where the electrode **16** is formed and the non-functional portion **158** around the element. Difference in light intensity may also occur among the non-functional portions **152**. As a result, light intensity is likely to be distributed unevenly throughout the chip. In the light emitting device of the present invention, uneven distribution of light intensity is mitigated by forming the protrusions **20** on the substrate surface. When the chip area increases, the region where the layer of the first conductivity type increases, and therefore propagation and loss of light tend to increase. This problem is also improved by forming the recesses or protrusions on the substrate surface. Thus the present invention is preferably applied to a light emitting device that has large area and a plurality of light emitting portions.

[0148] In the case of a light emitting device that emits light from the back of the substrate, it is preferable to form recesses or protrusions over the entire surface of the substrate. In case the electrode forming surface of the light emitting device **100** is connected to a base **104** (or element mounting surface or the like) as shown in **FIG. 22B**, for example, light can be extracted satisfactorily from the back surface of the substrate **10** by providing the protrusions **20** over the entire surface of the substrate **10**.

[0149] In the light emitting device of the present invention, recess and protrusion section **6***x*, **6***y* that functions as light extracting and light reflecting portion may be provided on the electrode forming surface as shown in **FIG. 25B**. Specifically, the recess and protrusion section **6***x*, **6***y* is formed on the surface of the semiconductor layer **101** outside the light emitting portion **151**, preferably along the side face of the light emitting portion **151**. The recess and protrusion section **6***x*, **6***y* can be formed by partial etching of the semiconductor layer **101**. For example, when the n-type layer **11** that becomes the electrode **16** forming surface by etching, the recess and protrusion section **6***x*, **6***y* may be formed at the same time. The light emitting device **100** shown in **FIG. 25A** is a variation of the light emitting element shown in **FIG. 10B** where recess or protrusion **6** is provided. Sectional view of **FIG. 25B** schematically shows a section along line A-A of the light emitting device shown in **FIG. 25A**.

[0150] As shown in **FIG. 26B**, the recess and protrusion section **6***x* is provided in a non-current injected portion **158** (non-functional portion) along the periphery of the light emitting device. The recess and protrusion section **6***y*, on the other hand, is provided in a functional portion (current injected portion) **157** between the electrode **16** of the layer of the first conductivity type and the light emitting portion **151**. More specifically, the recess and protrusion section **6***y* is provided in the light emitting device (functional portion **157**) along the side face of the light emitting portion **151** that is provided in singularity or plurality, between the electrode **16** and the light emitting portion **151**.

[0151] The recess and protrusion section **6***x* reflects light that emerges from the light emitting device mainly sideways, namely light that propagates horizontally from the light emitting portion **151**, and directs the light in the vertical direction, namely in a direction substantially perpendicular to the electrode forming surface. This increases the component of light perpendicular to the electrode forming surface. The recess and protrusion section **6***y* that is provided in the functional portion **157**, on the other hand, has the function to prevent light from being absorbed by the electrode **16** or being entrapped in other light emitting portion that is adjacent thereto, in addition to the function similar to that of the recess and protrusion section **6***x*. As a result, extraction loss of light can be reduced and the efficiency of light emission can be improved.

[0152] In the light emitting device of the present invention, it is preferable to provide the recess and protrusion section **6***y* between the light emitting portion **151** and the electrode **16**, and provide the protrusions **20** on the substrate surface that overlaps thereon. Particularly, in case the electrode **16** that is provided in a part of the non-light emitting portion **152** shields light emitted from the adjacent light emitting portion **151**, light can be effectively extracted by the cooperation of the recess and protrusion section **6***y* and the protrusions **20** to the outside of the device, especially in a direction perpendicular to the electrode forming surface. The recess and protrusion section **6***y* also has favorable effect on light propagating from the substrate side. That is, the recess and protrusion section **6***y* provided on the electrode forming portion **152** makes it difficult for light propagating from the substrate side to propagate toward the side face of the light emitting portion, thereby suppressing the light loss due to the electrode and the light emitting portion.

[0153] Side face of the recess and protrusion section **6***x*, **6***y* may also be formed in a shape similar to that of the side face of the protrusion **20** provided on the substrate surface. In this case, a method similar to that of forming the protrusions **20** on the substrate may be employed. The recess and protrusion section **6***x*, **6***y* formed on the semiconductor layer **101** has the function of extracting light that propagates in the layer, and the function to advantageously reflect the light that is extracted from the light emitting portion **151** located nearby to the outside. When the recess and protrusion section **6***x*, **6***y* is formed in a shape similar to that of the side face of the protrusion provided on the substrate surface, contact area of the bottom of the recess or protrusion and the inside of the element increases, thereby enabling it to extract more light from the inside of the element. Moreover, since the inclination angle of the side face of the recess and protrusion section **6***x*, **6***y* becomes smaller on the top face side, it is made possible to advantageously reflect the light, that propagates from the adjacent light emitting portion **151**, in a direction perpendicular to the substrate surface.

[0154] In case a plurality of light emitting portions **15** having complicated shape and/or structure are provided as shown in **FIGS. 9C, 10B, 22A** and **25A**, greater loss occurs when extracting light. The loss can be decreased by forming the functional recess and protrusion section shown as **6***x*, **6***y*. Also in a light emitting device where the light intensity is unevenly concentrated in a particular direction, uneven distribution of light can be improved by providing the protrusions **20** on the substrate and the recess and protrusion section on the semiconductor layer, so that the light emitting device having high directivity can be obtained. It is preferable to provide the recess and protrusion section like **6***x*, **6***y* so as to surround the light emitting portion **151** in the functional portion **157** of the light emitting device as shown in **FIG. 26B**. It is also preferable to provide the recess and protrusion section **6***x*, **6***y* so as to surround the electrode **16** that is provided in conjunction with the light emitting portion **151**. It is more preferable to provide the recess and protrusion section **6***x*, **6***y* on substantially the entire periphery. Particularly in case the light emitting portion is surrounded by other light emitting portions as shown in **FIG. 26A**, light tends to be trapped as the light emitting portion is surrounded by the adjacent light emitting portions. This loss can also be mitigated by the recess and protrusion section **6***x*, **6***y*. Most preferably, as shown in **FIG. 26A, 26B**, the recess and protrusion section **6***x*, **6***y* is provided so as to surround the light emitting portion **151** on almost the entire periphery, and also surround the electrode **16** on almost the entire periphery thereof.

[0155] As described previously, the recess and protrusion section **6***x*, **6***y* may be formed at the same time when the electrode forming surface **11***s* of the layer **11** of first conductivity type exposed by etching. This provides an advan-

tage with respect to the manufacturing process, since the recess and protrusion section **6***x*, **6***y* separated from the current injection electrode (for example, 14) and the light emitting portion **151** can be easily formed.

[**0156**] Bottom of the recess and protrusion section **6***x*, **6***y* may or may not correspond to the electrode forming surface **11***s*. For example, when the bottom of the recess and protrusion section **6***x*, **6***y* is located in the layer **11***b* of first conductivity type that is deeper than the electrode forming surface, light that propagates horizontally in the base layer **11***a* and light reflected from the substrate **10** can be extracted efficiently. It is particularly preferable that the recess and protrusion section **6***x*, **6***y* penetrates the layer **11***b* of first conductivity type and reaches the base layer **11***b,* namely reaches the depth where the non-functional portion is partly provided, and more preferably the recess and protrusion section **6***x*, **6***y* is formed at such a depth where the substrate is exposed. This makes it possible to isolate the layer **11***b* of first conductivity type and the base layer **11***a,* so that light propagating therein can be extracted efficiently. At this time, if the recess and protrusion section **6***x*, **6***y* is provided in the element **157** at the depth where the layer **11***b* of first conductivity type is partially or entirely removed, current diffusion path is interrupted. Therefore, it is preferable to divide the recess and protrusion section **6***y* in a plurality of regions in order to secure the current diffusion path. By providing the recess and protrusion section **6***y* in a fragmentary condition when viewed from above, the region between the portions of the recess and protrusion section **6***y* can be made the current diffusion path.

[**0157**] Various plan-view configurations and arrangements of the recess and protrusion section **6***x*, **6***y* may be employed similarly to the protrusions of the substrate. **FIG. 26A** shows triangular arrangement of circles similar to that of the protrusions shown in **FIG. 19A**. Light that has propagated horizontally in the device emerges from the side faces of the device in various directions. Therefore, it is preferable to provide the recess and protrusion section **6***x*, **6***y* so as to effectively obstruct the emergence of light in all directions from the side faces of the light emitting device. Specifically, it is preferable to provide the recess and protrusion section **6***x*, **6***y* periodically in two rows, more preferably three rows or more along the side face of the light emitting element as shown in **FIG. 26A**. Moreover, it is preferable to make the plan-view configuration of the recess and protrusion section **6***x*, **6***y* in substantially circular or oval shape so as to advantageously reflect light incident in various directions. Among the side faces of the recess and protrusion section **6***x*, **6***y*, the side face that faces the light emitting element is preferably a curved surface.

Embodiment 4 (Light Emitting Device)

[**0158**] The fourth embodiment is an element stack **103** comprising the light emitting element **100** mounted on a stack base **104** on the electrode forming surface thereof. Also the light emitting device made by packaging the light emitting element **100** or the element stack **103** will be described.

[**0159**] (Element Stack)

[**0160**] **FIG. 22B** is a schematic sectional view of the element stack **103**. The base **104** has a plurality of connection electrodes (not shown) each corresponding to the electrodes **14**, **16** of the light emitting element **100**, while being electrically insulated from each other. The electrodes and the light emitting structure that are separated from each other on the light emitting element side may also be electrically connected with each other by means of the electrodes of the base **104** side.

[**0161**] An element other than the light emitting element **100** may also be provided on the base **104**. Here, current, electrostatic protective element is formed in the base **104** as indicated by the equivalent circuit diagram of **FIG. 22C**, as shown in **FIG. 22B**. The current, electrostatic protective element is constituted from a p-type layer (the layer of the first conductivity type) **115***a* and a n-type layer (the layer of the second conductivity type) **115***b* provided in the base **104**. Two or more element portions may be provided on the base **104** and connected with the electrodes of the light emitting element **100** outside of the base and the mounting base **201** (**FIG. 24**). The protective element may be mounted on a mounting portion **222** in the light emitting device **200** and connected with the light emitting element (refer to **FIG. 24**).

[**0162**] The electrodes **14**, **16** on the light emitting element **100** side and the electrodes of the base **104** are connected via connecting member **114**. Alternatively, a part of the electrodes on the light emitting element **100** side or part of the electrode **112** on the base **104** side may be used as the connecting member. For example, a connecting layer may be formed instead of the pads **16***b*, **15***b* of the light emitting element **100**.

[**0163**] The base **104** may also be a sub mount such as heat sink that does not have element structure. The base **104** and the outside may be connected through connection electrode by wire bonding or the like. The electrodes of the element portion of the base **104** or the electrodes that connects the inside and the outside of the base may also be formed on the mounting surface and used as the electrodes or connection layer **114** for connecting the light emitting element.

[**0164**] (Light Emitting Device **200**)

[**0165**] **FIG. 23** and **FIG. 24** show light emitting devices comprising the light emitting element **100** or the element stack **103** on a device base. In the example shown in **FIG. 24**, two leads **210***a* and **210***b* are fastened onto the device base **220**. One of the leads, **210***a*, is the mount lead. The mount lead **210***a* functions as the mounting base **201**, and the light emitting element **100** (stack **103**) is mounted via the connection layer **114** (or the bonding layer **204**) in a housing portion (recess) **202** of the device base **201**. A side face **203** of the housing portion **202** of the mounting base **201** and a side face **221** of an opening **205** of the device base **220** function as light reflectors. The mounting base **201** that is the mount lead may also be used as a heat sink **205** for the light emitting element and connected to an external heat sink. The device base **220** also has the opening **225** in the light extracting surface **223**, so that the top face of the mounting base **201** is exposed through the opening **225** as a terrace **222**. The protective element and other elements may be mounted on the terrace **222**. The recess **202** of the mounting base **201** and the inside of the opening **225** of the device base **220** are filled with a translucent sealing member **230**. The lead electrode **210***b* comprises an inner lead **212***a* provided inside of the device base **220** and an external lead **212***b* that is an extension thereof to the outside of the device base **220**, so as to be connected with the outside thereby. The light

emitting element **100** (stack **103**) is electrically connected to the leads **210***a* and **210***b* via a wire **250** or the connection member **204**.

[**0166**] In the example shown in **FIG. 23**, the light emitting element **100** is mounted by means of a bonding member **204** on the mounting base **201** that is insulated from the leads **210***a* and **210***b*. A reflecting portion is provided on the recess side face **203** of the mounting base **201** that houses the light emitting element **100**. The mounting base **201** may also be connected to an external heat sink as the heat sink **205**. The light emitting element **100** is connected by the wire **250** to the leads **211***a* and **211***b*. The leads **210***a* and **210***b* are electrically connected to the outside via external leads **211***a* and **212***b*. Separation of the mounting base **201** and the lead **210** makes the light emitting device of excellent thermal design. The recess **202** of the mounting base and the opening of the device base **220** may be sealed with the translucent sealing member **230**. Light emission with desired directivity can be obtained by providing an appropriate optical system (lens) in the light extracting portion. The lens may be optically connected with the sealing member **230**. Or, alternatively, the sealing member **230** itself may be formed in the shape of lens.

[**0167**] (Light Converting Member)

[**0168**] A light converting member **106** or a light conversion layer **231** may be provided in the light emitting device as shown in **FIG. 23**. The light converting member **106** or the light conversion layer **231** absorbs a part of the light emitted by the light emitting element **100** and emits light of a different wavelength, and may contain a fluorescent material. The light converting member **106** or the light conversion layer **231** is formed so as to cover a part of the light emitting element **100** or as a whole thereof. Alternatively, the light converting member may also be formed as a coating film **105** that covers a part of the stack base **104** as shown in **FIG. 24**. For the binder of the fluorescent material, an oxide or a hydroxide that includes at least one element selected from a group consisting of Si, Al, Ga, Ti, Ge, P, B, Zr, Y, Sn, Pb or an alkaline earth metal is preferably used. The binder can be produced from an organometallic compound that includes at least one element selected from a group consisting of Si, Al, Ga, Ti, Ge, P, B, Zr, Y, Sn, Pb or an alkaline earth metal (preferably plus oxygen). The organometallic compound includes a compound having an alkyl group and an allyl group. Examples of the organometallic compound include metal alkoxide, metal diketonate, metal diketonate complex and metal carboxylate.

[**0169**] The light converting member may also be provided as part of the sealing member **230** of the light emitting device **200**. For example, the light converting member may be provided as a layer **231** provided on the sealing member **230***a* or between the sealing members **230***a* and **230***b*, apart from the light emitting element **100**, as shown in **FIG. 23**. Moreover, the entire sealing member **230** may also be used as the light converting layer by dispersing the light converting member in the sealing member **230**. The light converting member may also be provided as a sedimentation layer in the recess (housing portion) of the device base **220** or the mounting base **201**. Furthermore, as shown in **FIG. 24**, the light converting member may be included in the film **105** that covers the substrate where the protrusions are provided and/or the light emitting element **100**.

[**0170**] In case the coating film is provided on the surface of the substrate opposite to the element forming surface, namely the back of the substrate and the side face of the substrate, if there is a significant difference in the intensity of light emerging from the side face and the back surface of the substrate, color of the light produced by blending the converted light and the light emitted by the light emitting element varies depending on the direction (color unevenness). Particularly when two or more fluorescent materials, specifically two or more kinds of fluorescent material having different wavelengths of converted light are used for the light converting member, the problem of color unevenness becomes profound. The substrate having the protrusions **20** provided on the light emitting element of the present invention as described above can suppress the color unevenness. While the coating film **105** of the chip has been described, similar effects can be achieved also in the case of light converting member in the sealing member, or in the case of extracting light from the light emitting element side.

[**0171**] Examples of the fluorescent material described above are as follows. As the fluorescent material that emits green light, $SrAl_2O_4$:Eu, Y_2SiO_5:Ce, Tb, $MgAl_{11}O_{19}$:Ce, Tb, $Sr_7Al_{12}O_{25}$:Eu, (at least one of Mg, Ca, Sr and Ba) Ga_2S_4:Eu may be used. As the fluorescent material that emits blue light, $Sr_5(PO_4)_3Cl$:Eu; $(SrCaBa)_5(PO_4)_3Cl$:Eu; $(BaCa)_5(PO_4)_3Cl$:Eu; (at least one of Mg, Ca, Sr and Ba)$_2B_5O_9Cl$:Eu, Mn; (at least one of Mg, Ca, Sr and Ba) $(PO_4)_6Cl_2$:Eu, Mn may be used. As the fluorescent material that emits red light, Y_2O_2S:Eu; La_2O_2S:Eu; Y_2O_3:Eu; Gd_2O_2S:Eu may be used. The composition that includes YAG makes it possible to emit white light so as to greatly broaden the applications including the light source for illumination. YAG is a material represented by $(Y_{1-x}Gd_x)_3(Al_{1-y}Ga_y)_5O_{12}$:R (R is at least one element selected from Ce, Tb, Pr, Sm, Eu, Dy, Ho, and satisfies $0<R<0.5$), for example, $(Y_{0.8}Gd_{0.2})_3Al_5O_{12}$:Ce, $Y_3(Al_{0.8}Ga_{0.2})_5O_{12}$:Ce.

[**0172**] While nitride-based fluorescent material is used as the fluorescent material that emits reddish light in this embodiment, the light emitting device of the present invention may also provided with the YAG-based fluorescent material and a fluorescent material that can emit reddish light. Fluorescent materials that can emit reddish light are those which emit light upon excitation by light of wavelength from 400 to 600 nm, for example, Y_2O_2S:Eu; La_2O_2S:Eu; CaS:Eu; SrS:Eu; ZnS:Mn; ZnCdS:Ag, Al; ZnCdS:Cu, Al; etc. Use of the YAG-based fluorescent material and the fluorescent material that can emit reddish light enables it to improve the color rendering performance of the light emitting device.

[**0173**] The YAG-based fluorescent material formed as described above and the fluorescent material that can emit reddish light represented by nitride-based fluorescent material can be used in such a manner that two or more kinds thereof exist in one color conversion layer at the lateral side face of the light emitting device, or one or more kinds thereof exists in each of two color conversion layers. With such a constitution, light of mixed color can be obtained through mixing of light emitted by different kinds of fluorescent material.

[**0174**] Selecting the fluorescent materials as described above enables it to make a light emitting device that can emit light with various wavelengths with high efficiency of

extracting light. The light emitting device of the present invention is not limited to the visible region but may also be used for emitting ultraviolet ray together with a fluorescent material that is excited by the ultraviolet ray and emits visible light. Further, it can be applied to light of various wavelengths and electromagnetic radiation.

EXAMPLES

[0175] Now examples of the present invention will be described, but the present invention is not limited to these examples and may be applied to various other forms on the basis of the technical idea of the present invention.

[0176] Characteristics of the semiconductor light emitting elements having protrusions of forms A, B and C to be described below were evaluated with the results as shown in **FIGS. 20, 21**.

[0177] Sapphire substrates having principal plane in C plane and orientation flat surface in A plane are used.

[0178] In Example A, protrusions having a shape of equilateral triangle measuring about 5 μm in one side are formed at a distance of 2 μm (distance between adjacent sides) on the substrate surface. The protrusions are disposed in such an arrangement as sides of adjacent protrusions **20** oppose in substantially parallel to each other as shown in **FIG. 19D**. A parallelogram enclosed by dashed line **43** having interior angles of about 60° and 120° is regarded as unit cell that is repeated in the directions of axes **51, 52** periodically at equal intervals. Sides of the protrusions are formed in parallel to M-plane.

[0179] The protrusions are formed by a method shown in **FIG. 2, FIG. 18**. First, the protective film **25** that makes a mask is formed is formed from SiO_2 on the substrate and is shaped in a desired configuration by photolithography and RIE as shown in **FIG. 2B, FIG. 18A**. Then RIE etching is carried out by using $Cl_2/SiCl_4$ as shown in **FIG. 2C, FIG. 18B** (first step). Depth of etching is set to about 1 μm so that the protective mask **25** is almost totally removed. Then etching is continued so as to form the protrusions having two inclined surfaces as shown in **FIG. 2D, FIG. 18C** (second step). This results in the formation of the protrusions **20** having the first sloped surface **22** and the second sloped surface **23** as shown in **FIG. 5A**. Then as will be described later in Example 1, the base layer made of GaN in thickness of about 4 μm, the n-type layer such as n-type contact layer, the active layer and the p-type layer are formed on the substrate to make the semiconductor element. The n-type layer is partially exposed to form the n-type electrode therein. The transparent electrode of Ni/Au is formed over substantially the entire surface of the p-type layer thereby making the light emitting element.

[0180] Example B is a variation of example A where the protrusions of the substrate are formed in circular shape as shown in Example 1, **FIG. 4A, FIG. 19A** and **FIG. 19B**. Protrusions having diameter of 4 μm are arranged at intervals of 1.5 μm. A parallelogram enclosed by dashed line having interior angles of about 60° and 120° is regarded as unit cell **53** that is repeated in the directions of axes **51, 52** periodically as shown in **FIG. 19A**.

[0181] Example C is a variation of the substrate manufacturing process of Example B where the second step of etching is followed by RIE etching with CF_4 as the third step so as to form the side face (curved surface protruding toward the outside) as shown in **FIG. 18D, FIG. 15** and **FIG. 16A**.

[0182] The following results are obtained through observation of the surface and measurement of the element characteristics of the Examples A, B and C having the protrusions formed in different patterns as described above. Electrostatic destruction characteristic is shown in **FIG. 20**. Graph **61** shows the electrostatic withstanding voltage in the forward direction and graph **62** shows the electrostatic withstanding voltage in the backward direction. Examples A and B shows substantially the same electrostatic withstanding voltage in the forward direction, with Example B showing less data dispersion in the characteristics than Example A. Example C shows remarkably higher electrostatic withstanding voltage than Examples A and B. It can be seen that Example C shows small data dispersion comparable to that of Example B.

[0183] In terms of electrostatic withstanding voltage in the backward direction, too, Example A and Example B are comparable similarly to the case of forward direction, while Example C showing greatly improved electrostatic withstanding voltage. It can be seen that circular shapes of Examples B and C show less data dispersion in the characteristics than the triangular shape of Example A. Electrostatic withstanding voltage was measured under the conditions of 200 pF and 0 Ω. Breakdown voltage was measured on 10 pieces of each Example. Mean value, maximum value (maximum value is evaluated as "2500 V" if a sample is not destroyed at 2500 V) and minimum value of the measurements are plotted as shown in the graph of **FIG. 20**.

[0184] Measurements of luminance of the light emitting element chips in the Examples show that Example B has slightly higher luminance than Example A as shown in **FIG. 21**. Output power is significantly higher in Example C than in Examples A and B, showing improvement of about 14% over Example A. With regards to Vf, Example B shows a value 0.02 V higher and Example C shows a value about 0.06 V higher than that of Example A. Variability of wavelength of emitted light within a wafer is comparable among the Examples.

[0185] Conditions of the wafers whereon the semiconductor is formed are observed with an optical microscope for pits and are observed with TEM for threading dislocation, in order to compare the crystallinity among the Examples. Example A shows many pits with a high density, showing unsatisfactory crystal growth in a large region. Example B shows less pits as a whole than Example A, showing unsatisfactory crystal growth in a smaller region. In Example C, pits are hardly observed, and unsatisfactory crystal growth is observed in only smaller region. In Example A, voids **44** are observed at near the center of opposing sides of the triangular protrusions as shown in **FIG. 19D**. Observation of a cross section shows that occurrence of threading dislocation is less and crystallinity is better in Example A than in Example B. Inclination angle θ_m of the entire sloped surface of the protrusion observed with SEM is from about 65° to 70° in Example B and from about 45° to 50° in Example C.

[0186] This suggests that smaller inclination angle increases the effect of extracting light and improves the efficiency of light emission in Example C. In Example C, it is supposed that the notch **27***a* shown in **FIG. 18F** is

smoothed in the third step, and the side faces of the protrusions are smoothed (refer to **FIG. 16**) so as to form the curved surface **26**, thus resulting in reduced pits in the semiconductor layer, reduced threading dislocation and reduced unsatisfactory growth. As a result, higher yield, less variability and higher output power are obtained in Example B than in Example A, and in Example C than in Example B.

[0187] Observation of the inclination angle θ_m of the entire sloped surface of the protrusion and surface condition of the side face of the protrusion while changing the etching condition in Example C shows as follows. When the duration of etching in the third step is made longer, the inclination angle continues to decrease while craters appear due to damage by etching on the top face of the protrusion, flat surface between the protrusions and the side face of the protrusion, with deteriorating crystallinity. Thus it is desirable to set a proper duration of etching. Then the etching gas used in the third step is changed. With Ar gas, shape of protrusion and electrostatic withstanding voltage that are intermediate between Examples A and C are obtained, and the inclination angle of the protrusion is about 60°. When $SiCl_4$ is used as the etching gas, the inclination angle is about 70°, slightly decreasing from the second step, while only a part on the top face side is turned into a curved surface. When etching with $SiCl_4$ gas is added following the third step of Example C, protrusions having inclination angle of about 50°, comparable to that of Example C are obtained. When $SiCl_4/Cl_2$ gas is used in the etching of the third step, inclination angle of about 58°, which is larger than that of Example C, is obtained. A decreasing trend of the radius of curvature of the curved surface on the side face of the protrusion is also observed. From the findings described above, it is preferable to use CF_4 and Ar as the etching gas in the third step.

Example 1

[0188] A sapphire substrate of which principal plane lies in C plane (0001) having orientation flat in A-plane (11-20) is used as the substrate. First, a SiO2 film **25** is formed on the sapphire substrate **10** to make an etching mask as shown in **FIG. 2A**.

[0189] Then a round photo mask having diameter of 5 μm is used to etch the protective film **25** made of SiO2 and the sapphire substrate **10** to a depth of 1 μm by RIE as shown in **FIGS. 2B, 2C**. After removing the protective film **25**, surface of the sapphire substrate **10** is further etched so as to form a repetitive pattern of protrusions **20**, shown in **FIG. 2D**, having sloped surfaces formed in two steps (regions that are not etched are indicated by hatching). Diameter of the top surface of the protrusion **20** is 3 μm and distance between adjacent protrusions **20** is 1.5 μm. Angle of inclination θ_1 of the first sloped surface **22** on the side face of the protrusion **20** is 70°, and angle of inclination θ_2 of the second sloped surface **23** is 20° (FIG. **12**).

[0190] On the sapphire substrate **10** whereon the repetitive pattern of the protrusion **20** has been formed, a low-temperature growth buffer layer of $Al_xGa_{1-x}N$ ($0 \leqq x \leqq 1$) is formed to a thickness of 100 Å, a GaN layer is formed to a thickness of 3 μm, a Si-doped GaN layer to a thickness of 4 μm and a GaN layer is formed to a thickness of 3000 Å, as the n-type semiconductor layers. Next, the active layer of multiple quantum well structure is formed to make the light emitting region by forming 6 well layers of InGaN each 60 Å thick and 7 barrier layers of Si-doped GaN each 250 Å thick alternately. The barrier layer to be formed last may be undoped GaN. By forming the first layer made of undoped GaN on the low-temperature growth buffer layer, the protrusions **20** can be embedded more uniformly so as to obtain high crystallinity of the semiconductor layer to be formed thereon.

[0191] After forming the active layer of multiple quantum well structure, 200 Å of Mg-doped AlGaN, 1000 Å of undoped GaN and 200 Å of Mg-doped GaN are grown as the p-type semiconductor layer. The undoped GaN layer formed as the p-type semiconductor layer shows the property of p-type due to Mg diffusing therein from the adjacent layer.

[0192] Then the Si-doped GaN layer is exposed by etching from the Mg-doped GaN, the p-type semiconductor layer, the active layer and part of the n-type semiconductor layer, so as to form the n electrode.

[0193] Then transparent p electrode made of Ni/Au is formed over the entire surface of the p-type semiconductor layer, and the p pad electrode made of W/Pt/Au is formed on the transparent p electrode at a position opposing the exposed surface of the n-type semiconductor layer. The n electrode made of W/Pt/Au is formed on the exposed surface of the n-type semiconductor layer.

[0194] Last, the wafer is divided into rectangular chips so as to obtain semiconductor chips measuring 350 μm square. The semiconductor chip is mounted on a lead frame that has a reflector, thereby making a bullet-shaped LED. The LED emits light having wavelength of 400 nm with output power of 14.0 mW for a forward current of 20 mA.

Comparative Example 1

[0195] A bullet-shaped LED was made similar to Example 1 except for forming recess or protrusion in single step on the surface of a sapphire substrate as a Comparative Example. Output power of the LED was 9.8 mW for a forward current of 20 mA.

Example 2

[0196] A sapphire substrate of which principal plane lies in C plane (0001) having orientation flat in A-plane (11-20) is used as the substrate. A protective film is used to form circular protrusions having diameter of 3 μm on the sapphire substrate **10**. Diameter of the top surface of the protrusion is 2 m and distance between adjacent protrusions is 1.0 μm. Angle of inclination θ_1 of the sloped surface on the side face of the protrusion is 70°, and angle of inclination θ_2 is 20°. The protrusions are formed in a pattern shown in **FIG. 7B**. With other respects, this Example is similar to Example 1. Output power of the LED thus obtained was 14.0 mW for a forward current of 20 mA.

Example 3

[0197] Projections are formed on a substrate under the following conditions. With other respects, this Example is similar to Example 1. Photo mask having a shape of equilateral triangle measuring 5 μm along one side is aligned so that one side of the equilateral triangle is perpendicular to the orientation flat. After etching the protective film **25** made of SiO_2 and the sapphire substrate **10** to a depth of 1 μm by

RIE so that the sides of the equilateral triangle become substantially parallel to M-planes (1-100), (01-10) and (−1010) of sapphire as shown in **FIGS. 2B, 2C**, the protective film **25** is removed. Surface of the sapphire substrate **10** is further etched so as to form the repetitive pattern of protrusions **20** shown in **FIG. 2D**. Length a of one side of the top surface of the protrusion is 2 μm and distance b between adjacent protrusions is 1.5 μm. Angle of inclination θ_1 of the side face of the protrusion is 70°, and angle of inclination θ_2 is 20° (**FIG. 13**). Output power of the LED thus obtained was 12.0 mW for a forward current of 20 mA.

[**0198**] The present invention has been fully described by way of preferred embodiments while making reference to the accompanying drawings. Various variations and modifications of the present invention are apparent to those skilled in the art. Such variations and modifications are understood to fall within the scope of the present invention to the extent that does not deviate from the appended claims.

1-27. (canceled)

28. A semiconductor device comprising:

a substrate having recesses and/or protrusions formed on the surface thereof, and

semiconductor layers made of material different from that of said substrate and formed on the surface of said substrate,

wherein a side face of said recesses and/or protrusions includes at least two surfaces having different inclination angles.

29. The semiconductor device according to claim 28, wherein the side face of said recesses and/or protrusions has at least a first surface on a lower side and a second surface on an upper side, with inclination angle θ_1 of said first surface being larger than inclination angle θ_2 of said second surface.

30. The semiconductor device according to claim 29, wherein roughness Ra_1 of said first surface is larger than surface roughness Ra_2 of said second surface.

31. The semiconductor device according to claim 29, wherein the inclination angle θ_1 of said first surface is larger than 45° and smaller than 90°.

32. The semiconductor device according to claim 29, wherein said substrate is made of a material selected from the group consisting of sapphire, Si, SiC and spinel, and said recesses and/or protrusions have circular, triangular, parallelogram or hexagonal profile in plan view.

33. The semiconductor device according to claim 29, wherein said semiconductor device is a semiconductor light emitting device.

34. The semiconductor device according to claim 28, wherein said recesses and/or protrusions are formed in repetitive pattern.

35. The semiconductor device according to claim 28, wherein the side face of said recesses and/or protrusions has a curved surface.

36. The semiconductor device according to claim 35, wherein the side face of said recesses and/or protrusions has inclination angle Ra_b on a lower side and inclination angle Ra_u on an upper side, the inclination angle Ra_b being larger than the inclination angle Ra_u.

37. The semiconductor device according to claim 35, wherein the side face of said recesses and/or protrusions has a curved surface that is convex toward the outside of the protrusion and/or the inside of the recess.

38. The light emitting device according to claim 28, wherein the side face of said recesses and/or protrusions has notches and width of said notches is larger on a lower side than on an upper side and/or the number of said notches is larger on a lower side than on an upper side.

39. A light emitting device having semiconductor light emitting element on a substrate that has protrusions separated from each other and disposed periodically, wherein width of cross section of said protrusion is larger on the bottom side than on the top face side, and inclination angle of the side face of said protrusion is smaller on the top face side than on the bottom side; and

wherein, with a circle that is in plane with the substrate surface and circumscribed with the side faces of two closest protrusions being referred to as a first circle, a circle that is in plane with the substrate surface and circumscribed with the side faces of at least three protrusions being referred to as a second circle and a circle that is in plane with the top surface of said protrusions and circumscribed with the side faces of two closest protrusions being referred to as a third circle, the diameter of said second circle is larger than the diameter of said first circle and smaller than the diameter of said third circle.

40. The light emitting device according to claim 39, wherein the side face of said protrusion has a curved surface that is convex toward the outside.

41. The light emitting device according to claim 40, wherein said third circle and said second circle overlap each other.

42. The light emitting device according to claim 41, wherein the bottom of said protrusion is circular, and said protrusions are disposed periodically at substantially the same intervals in two axial directions that intersect with an angle of about 60° in the substrate surface.

43. A method of manufacturing a substrate for a light emitting device that has a plurality of protrusions and/or recesses, comprising:

a first step of etching a part of the substrate with a protective film provided on the substrate and forming protrusions and/or recesses having side faces; and

a second step of exposing and etching the side face of said protrusions and/or recesses, at least a part of the top faces of said protrusions and/or at least a part of the top surface of the substrate between said recesses, so as to make the inclination angle of the side face of said recesses and/or protrusions on an lower side larger than the inclination angle on an upper side.

44. The method of manufacturing a substrate for the light emitting device according to claim 43, wherein said second step is followed by a third step where the side faces of said protrusions and/or recesses, at least a part of the top faces of said protrusions and/or at least a part of the top surface of the substrate between said recesses are exposed and etched, so as to turn the side faces into curved surfaces.

45. The method of manufacturing a substrate for the light emitting device according to claim 44, wherein said protrusions are provided in plurality, and top faces and/or bottom of said protrusions are circular.

46. The method of manufacturing a substrate for the light emitting device according to claim 43, wherein the protective film is also removed in said first step of etching.

47. The method of manufacturing a substrate for the light emitting device according to claim 43, wherein a plurality of notches are formed on the side face of said protrusions and/or recesses in said first step, and width of said notches in said side face is larger on a lower side than on an upper side and/or the number of said notches is larger on a lower side than on an upper side.

* * * * *